

GRENFELL TOWER: PHASE 1 REPORT



Prof. José L. Torero CEng, RPEQ, FREng, FRSE, FTSE, FIFE, FSFPE, FICE, FCI

23rd May 2018

1 EXECUTIVE SUMMARY

2 A fire originated in the kitchen of Flat 16 of Grenfell Tower on June 14th, 2017. While there are
3 numerous ways in which this fire could have originated, at the date of submission of this report, there
4 is no conclusive evidence that constrains the cause, origin and initial stages of the fire to a single
5 timeline or set of events. Nevertheless, analysis of the evolution of the events and of the observable
6 damage enables a detailed analysis of many of the factors influencing the nature of the event and its
7 consequences.

8 Fires evolve in space and time leading, in many instances, to a complex sequence of events and
9 multiple processes and activities occurring simultaneously. It is therefore useful to structure these
10 events, processes and activities. So, for the purpose of this report, the timeline of the Grenfell Tower
11 fire will be divided into four stages, each of which reflects a key phase in terms of this particular fire
12 event¹:

- 13 • **First Stage:** From the initiation of the event to the breaching of the compartment of origin
- 14 • **Second Stage:** From the breaching of the compartment of origin to the point when the fire
15 reaches the top of the building
- 16 • **Third Stage:** The internal migration of the fire until the full compromise of the interior of the
17 building, including the stairs
- 18 • **Fourth Stage:** The untenable stage²

19 The geometrical configuration of the kitchen and the available ventilation did not allow the kitchen
20 fire to attain flashover. The temperature of the smoke accumulated below the ceiling of the kitchen
21 will remain within the approximate range of 100-220°C. As will be described below, these
22 temperatures are capable of damaging components of the window, but the accumulated smoke
23 cannot ignite any of the combustible materials in the vicinity of the window or within the façade
24 system.

25 The temperature of the smoke accumulated below the ceiling of the kitchen is sufficient to heat the
26 uPVC components of the window to temperatures that result in complete loss of mechanical
27 properties (90°C). These temperatures would have been attained within an approximate period

¹ The stages are qualitative in nature therefore no exact times are proposed here, details on times can be found in the body of the report and in references [2], [4] and [5]. The times are roughly First Stage (00:54 - 01:05), Second Stage (01:05 - 01:30), Third Stage (01:30 - 02:30) and Fourth Stage (02:30 - extinction).

² The term tenability is intended to describe in a qualitative manner, the conditions within different parts of the building as it pertains to the interactions of the fire and smoke with people. Tenability and safety are difficult terms to define and therefore have to be interpreted in a relative manner. That is because the concept of tenable conditions inside a building will vary between different persons e.g. between adults and children and it is possible to adopt very technical definitions of tenability depending on what is being assessed. For the purpose of this report, I use the phrase untenable conditions to mean conditions that are life-threatening (e.g. high temperatures, high concentration of carbon monoxide, etc.) or perceived by occupants as life-threatening (e.g. poor visibility). In contrast, a tenable or safe environment will be one where conditions remain or are perceived by occupants not to be life threatening. Typical approaches and quantitative data that serve to define tenability are provided in the literature [6] but for the purpose of this report only the qualitative approach described above will be used.

between 5-12 min which is consistent with the time available between the discovery of the fire (initial call to the fire brigade) and the first observation of smoke and burning debris external to the building. The geometry of the uPVC elements and approach used for their fixation would have resulted in the eventual fall-off of these elements. The failure of the uPVC leaves all other combustible components of the façade system exposed.

Flames have higher temperatures than the smoke accumulating below the ceiling of a room. Therefore, an unobstructed fire of 300 kW placed at a maximum distance of 3.1 m from the window would have been sufficient to ignite any of the combustible components of the façade system. A fire of 300 kW is no greater than a fire originating from a pan fire of 40-50 cm radius. A pan fire will cover its entire surface immediately after ignition so it will remain of constant size. In contrast, a fire originating from appliances will ignite and then spread through the different combustible materials within the appliance, thus the fire will grow in time. Appliances with significant mass of combustible materials (e.g. refrigerators) can release heat beyond 1000 kW, while those with less mass of combustible materials (e.g. electrical stoves) might never reach 300 kW.

If the fire was obstructed (i.e. there was an obstacle between the fire and the window) then a 300 kW fire would have had to be placed less than 1 m from the combustible materials of the window if those materials were to ignite. A fire placed further away, capable of igniting combustible materials in the window, would have most likely brought the room to flashover.

Almost any appliance within a common kitchen could have sustained a fire of the size (300 kW) required to ignite combustible components of the façade system if placed close enough to the window. Therefore, the cause and origin of this fire is of minor importance to the outcome. To complete an investigation, it is important to understand how and where the fire started. Nevertheless, the precise cause and origin of this fire is, on one respect, irrelevant to the event which subsequently occurred. From a design perspective, a fire of 300 kW occurring in a residential kitchen, and in the proximity of the window, should be considered to have a probability of one. In other words, a fire of this nature will happen in a residential unit and therefore the building is required to respond appropriately.

Once any of the combustible components of the façade ignited, their proximity and complex arrangement would have inevitably resulted in the ignition of other components leading to external flame spread. This point marks the end of the first stage of the fire.

Through this first stage of the fire the building was operating as intended and in accordance with the assumptions which underpin the existing regulatory framework. Firefighting operations remained within the bounds of conventional practice and the structure could be considered to pose no risk of failure. A “stay put” strategy (i.e. occupants of flats adjacent to the flat on fire or on levels above or below can remain safely within their own flat) would have implied minimum risk to the occupants during the first stage of the fire.

Vertical fire spread characterizes the second stage of the fire. Vertical flame spread is significantly faster and more robust than lateral flame spread, so the fire rapidly propagates upwards but propagates laterally with greater difficulty.

Only in the final 5 – 10 minutes of the second stage (from 01:20 onwards) and before the fire reaches the top of the East façade, was there a significant number of emergency calls indicating smoke or flames within the building. These calls were not related to the original kitchen fire. Video camera

recordings show that during this period, occupants were, for the most part, able to egress with little or no evidence of smoke. With the exception of some short time periods, it can be concluded that the stairs remain safe during this stage of the fire. The moment when the fire reaches the top of the building is defined here as the end of the second stage of the fire.

Through this second stage of the fire the building is operating outside the conditions contemplated by the existing regulatory framework. Firefighting operations are outside the bounds of conventional practice and therefore have to be driven by a dynamic risk assessment. A “stay put” strategy is not consistent with the characteristics of the second stage. To a large extent the building remains tenable and the stairs still retain the characteristics required for them to be a safe egress path. Egress is outside the bounds of conventional protocols, therefore is not free of risk, but nevertheless it can be considered a better strategy than “stay put.” The heating period from the fire, even if an extreme heating rate is considered, is too short to result in structural temperatures that would have posed any challenge to the integrity of the structure. The structure can be deemed safe in this period.

Cavity barriers, no matter how well or badly they were designed and / or implemented, would not have prevented vertical or lateral flame spread in the Grenfell Tower fire. Flames can propagate through the interior cavities of the façade system but can also project over the façade system. Flames in the interior cavities will face and be slowed by the cavity barriers. Flames projected over the façade system will spread unobstructed via the exterior (this includes joints, damaged areas, etc.). Typical flame temperatures are higher than the melting temperature of aluminium (650°C) therefore the aluminium plates of the composite panels would have offered no protection to the combustible materials.

Details of the cladding will have an impact on flame spread rates, although in the case of Grenfell Tower, upward flame spread rates are not uniquely fast. A comparison with other international events shows that upward flame spread for the Grenfell Tower is among the slowest. It is therefore possible to ascertain that detailing of the façade system (as opposed to its material composition) has only a minor impact on the evolution of this fire.

Lateral spread in the initial stages of the fire is much slower than vertical flame spread. Once the fire reaches the top of the building, the fastest rate of spread occurs in the area of the architectural crown. Lateral flame spread results in significant amounts of debris falling downwards igniting the façade system in lower floors of the building. All these fires then proceeded to propagate upward. Therefore, the main mechanism of lateral fire spread is falling debris, and thus the rate of lateral spread is defined by the rate of lateral spread of the fire at the architectural crown.

Different details in the façade system (materials, geometry, cavity barriers, etc.) seem to show different levels of impact on the rate of flame spread. Tests conducted after the Grenfell Tower fire do provide some further information. But the complexity of this façade system is such that observations and tests, such as BS 8414, do not provide sufficient information to be able to reach incontestable conclusions. The specificity of the scenario used for these tests and the quantity and quality of the data recorded does not allow for a reliable extrapolation of the test results. Adequate performance assessment of systems of the complexity of these façade systems require better and more detailed data for a range scenarios and test configurations.

110 Compliance of the façade design relies on establishing if it “adequately resists the spread of fire.”³ The
111 only path to compliance is performance assessment “from test evidence”⁴ used by a competent
112 engineer using “relevant design guides.”⁵ The complexity and importance of the façade system
113 requires more than guides and therefore the reliance is fully on professional competency. There is no
114 clear definition of professional competency, therefore this is a matter that needs to be studied with
115 great attention.

116 There are no provisions in the Building Regulations that require the designer to control inward
117 penetration of an external fire occurring on the building. Emphasis is given to the risk posed by heat
118 fluxes of a magnitude typical of those received from adjacent buildings (12.6 kW/m²). Furthermore,
119 given that glazing is an unavoidable part of the function of a residential building it is certain that in the
120 presence of an impinging external flame the glazing will fail. Glazing is generally considered to fail with
121 heat fluxes of 5 - 10 kW/m² while external fires occurring on the building have been measured to
122 deliver heat fluxes within a range of 20-120 kW/m². It is therefore not reasonable to expect that an
123 external fire occurring on the building will not start internal fires within the building.

124 In the third stage of the Grenfell Tower fire, internal fires were started at multiple levels as the fire
125 propagated upwards. In a similar manner, but at a much slower rate, internal fires would have been
126 initiated after the fire propagated laterally. Grenfell Tower had multiple pathways for internal
127 propagation, many of them much less robust than glazing (i.e. the extraction fan, window detailing,
128 etc.) and they all contributed to fast ingress of flames into the units.

129 Analysis of the emergency calls and a damage analysis shows that internal penetration happens in
130 many ways, with a wide range of consequences and in many different locations. Internal penetration
131 occurs first in floors 5, 12 and 22. Rapid internal penetration above floor 20 can be attributed to the
132 presence of the architectural crown and the debris falling from it. Due to immediate proximity to the
133 architectural crown, the upper floors were more readily exposed to the build-up of falling debris on
134 external ledges. Furthermore, a buoyant plume will carry heat upwards further explaining the rapid
135 ingress of flames into the units above floor 20.

136 Analysis of other international fire events shows that the buoyant plume generated by the fire cannot
137 significantly accelerate lateral fire spread in the absence of other contributing factors. Several
138 international fire events show that once the fire reaches the top of the building it starts to decay,
139 showing only minor lateral fire spread. In some cases, extensive lateral fire spread similar to Grenfell
140 Tower occurred. Most international events are poorly documented therefore it has not been possible
141 to identify any design features that are consistent to all fires where significant lateral fire spread
142 occurred. Nevertheless, the fire occurring at the Monte Carlo Hotel & Casino in Las Vegas showed
143 rapid lateral propagation at the top of the building. This fire serves as an example that illustrates how
144 debris from a high-level fire can initiate multiple lower fires creating lateral fire spread over a more
145 extensive area of the building.

146 Once the external fires have breached the exterior of further units, they may or may not act as an
147 ignition source for a compartment fire, depending on the layout of the fuel within the breached
148 compartment and the location of the ignition point. At Grenfell Tower, and increasingly with height,

³ Functional requirement B4 (ADB) and performance criteria specified in Section 12.5 (ADB).

⁴ Section 12 of ADB and Appendix A of ADB bullet point (b).

⁵ Section 12 of ADB and Appendix A of ADB bullet point (b).

149 the internal fires developed into post-flashover fires, rapidly filling the units with smoke and involving
150 combustible materials within the units.

151 At this point the boundary of the units (i.e. perimeter walls and doors) should act as barriers to the
152 progression of smoke. Several international events have shown that means of egress can be protected
153 effectively by means of compartmentalization⁶. Very large fires, with comparable internal fire spread,
154 have not resulted in penetration of smoke and flames into the stair lobby or stairs.

155 Compartmentalization is a required part of the Building Regulations and it is a critical feature of the
156 design of high-rise buildings. Furthermore, ventilation may be necessary to provide a redundancy that
157 protects the stair lobby⁷. The stairs are further protected by a second redundancy consisting of the
158 stair enclosure (including the doors). Therefore, there is an expectation that smoke can still be
159 prevented from entering the remaining safe area of the building (i.e. the stairs).

160 It has been reported that samples of the Grenfell Tower doors failed a standard test approximately 15
161 minutes into the test. The standard test does not replicate a fire event (in terms of the progression of
162 the fire) but creates conditions whereby there is a steady growth of the temperature in time. In 15
163 minutes the temperature of the standard test would have reached approximately 740°C. In a real fire,
164 740°C is a temperature characteristic of a post-flashover fire. Therefore, it is possible to infer that
165 failure of the doors leading to the lobby would have occurred only after the units would have been
166 fully involved in the fire (post-flashover fire).

167 A feature of these doors is that they are of combustible construction resulting in ignition at failure. If
168 the doors ignite they would have inevitably compromised the lobby. Given such a fire, the cross-
169 ventilation strategy (even if it was operational and well maintained) would not have served as an
170 effective redundancy. Because of the small dimensions of the lobby and the fact that it was
171 surrounded by multiple units burning, it is very likely that the stair doors would have been challenged
172 by impinging flames. Impinging flames would have provided enough heat to possibly challenge the
173 performance of any doors similar to those tested after the Grenfell Tower fire.

174 Inspection of all the doors shows that areas where there was major fire impact (i.e. evidence of high
175 temperatures and significant soot deposition) correlate well with areas where doors are either missing
176 or significantly damaged. Other potential paths for smoke and flames have been identified (e.g.
177 inadequate fire stopping material surrounding service penetrations, absent door seals, etc.)
178 nevertheless no significant compartmentalization deficiencies could be established in the post-event
179 inspections. While any deficiency could have contributed to the migration of smoke into the lobby, it
180 would have been highly unlikely that flames could have migrated into the lobby via these routes to
181 create conditions that could compromise the doors separating the lobby from the stairs.

182 A feature of the Grenfell Tower fire was the observation of smoke escaping from windows opposite
183 to the initial location of the fire (i.e. escaping via the west and south faces of the building). These
184 observations occur as early as 40 min from the reporting of the initial fire in Flat 16. Migration of
185 smoke across the building would have required at least two breaches of barriers that were separated
186 from each other (i.e. two flat entrance doors). No clear explanation can be proposed, nevertheless,

⁶ Compartmentalization is a process by which physical barriers (ex. walls, floor slabs, doors, etc.) that can withstand the effects of a fire (for a sufficient period of time) are used to maintain the fire within a unit, therefore not allowing heat and smoke from entering adjacent areas of the building.

⁷ Section 2 – Means of Escape from Flats (ADB).

187 given the information available, it is most likely that this occurred because doors were open. This
188 highlights the importance of self-closing mechanisms for doors.

189 Once the fire has re-entered the building, compartmentalization is the main line of defence. Compliant
190 systems would have helped to protect egress paths and deliver safe paths for the occupants to
191 evacuate. While the external fire contributes to ignition of the unit furnishings, the energy
192 contribution to the unit from this external fire is limited and localized to the areas around the window.
193 Thus, there is no reason for compartmentalization requirements designed to withstand a post-
194 flashover fire not to be suitable for a fire of the nature of that of Grenfell Tower.

195 Occupant movement (combined with potential absence of functioning self-closers and therefore
196 leaving doors open) or firefighting operations most likely had an impact on the capability of smoke
197 and flames to migrate from the units towards the lobby and stairs. Nevertheless, this possibility cannot
198 exonerate the need for compliant compartmentalization features (walls, fire doors, fire stop, etc.).

199 The migration of building occupants was analysed showing that the patterns of descent varied in time.
200 First, people reported a dynamic evolution of the smoke within the building. Within some time periods
201 people migrated downwards showing that the stairs still remain tenable. At other points in time
202 people migrated upwards, reporting that the stairs were filled with smoke. Through the third stage of
203 the fire, tenability evolves in a dynamic manner as the fire spreads laterally and different failures
204 occur. In this period, most of the calls reporting smoke and flames come from floors 10-15 and above
205 floor 20.

206 Between approximately 60 and 70 min from the initiation of the fire, reports of smoke in the lobby
207 and fire and smoke in units become more generalized. This marks the end of the third stage and can
208 be considered as a point when there is generalized loss of tenability in the building.

209 Through this third stage of the fire, the building is operating outside the conditions contemplated by
210 the existing regulatory framework. Firefighting operations are outside the bounds of conventional
211 practice. The magnitude of the event has significantly reduced the capacity of the fire service to
212 manage the situation. A thermal analysis of the structure shows that the structure was still safe.
213 Temperatures of the structure would have not reached magnitudes where significant damage would
214 have been expected. A “stay put” strategy is not consistent with the characteristics of the third stage.
215 Tenability of the egress paths is highly questionable therefore egress and rescue both represent a high
216 risk during this stage.

217 Stage four is characterized by multiple calls indicating critical conditions. Many sectors of the building,
218 including lobbies and stairs are untenable. This stage will also be characterized by multiple forms of
219 failure that could potentially include breaches of the gas lines, penetration of fire stopping, structural
220 deterioration, etc. Given the potential temperatures of the structure, a detailed structural assessment
221 would have been essential to establish the stability of the building. This type of assessment requires
222 inspection and analysis not possible during fire rescue and response activities. During this stage, egress
223 or rescue operations are probably still possible within some sectors of the building, nevertheless these
224 activities would be implemented well outside the scope of any regulated practices and will imply
225 significant risk for occupants and fire fighters. The fourth stage does not guarantee safe firefighting
226 operations inside the building.

227 The tragic consequences of the Grenfell Tower fire highlight the significant shift in complexity that
228 occurs when intricate façade systems are incorporated into high rise buildings. Functional

229 requirements, guidelines and simple standardized tests become insufficient tools to establish
230 adequate performance⁸ of systems where performance is a function of the interactions of the building
231 and building envelope.

232 The inadequacy of these methods of performance assessment / regulation is such that systems that
233 introduce obvious dangers can be incorporated by designers in a routine manner. These systems can
234 be used without necessitating sufficient consideration of the effect that that inadequate performance
235 can have on the overall validity of the fire safety strategy⁹. This is despite the explicit understanding
236 that one of the fundamental assumptions backing almost all aspects of a tall building fire safety
237 strategy is that external fire spread shall be prevented.

238 The regulatory framework relies very heavily on competent professionals to provide the necessary
239 interpretation that will bridge the gaps and resolve the ambiguities left by functional requirements,
240 guidelines and standardized tests. Nevertheless, a competent engineer should be capable of
241 interpreting the requirement to “adequately resist the spread of fire over the walls ... having regard
242 to the height, use and position of the building¹⁰” within the context of the needs of the fire safety
243 strategy in the case of a specific tall building. In the case of the fire safety strategy of Grenfell Tower,
244 “adequately resist” should have been interpreted as being “no” external fire spread.

245 There is currently no definition of what is the competency required from these professionals, or skill
246 verification approaches that should be used, so as to guarantee that those involved in the design,
247 implementation, acceptance and maintenance of these systems can deliver societally acceptable
248 levels of safety. There is a need to shift from a culture that inappropriately trivializes “compliance” to
249 a culture that recognizes complexity in “compliance” and therefore values “competency,”
250 “performance” and “quality.” Otherwise, the increasing complexity of building systems will drive
251 society in unidentified paths towards irresponsible deregulation by incompetency.

⁸ Performance is defined as adequately fulfilling all functions that support and enable the fire safety strategy to deliver an acceptable level of safety.

⁹ Fire Safety Strategy, as referred here, is not a specific document but a conceptual representation of the ensemble of measures introduced to guarantee adequate fire safety (Section 1.6)

¹⁰ Section B4. (1) External Fire Spread (ADB).

CONTENTS

| | |
|--|----|
| Executive Summary..... | 2 |
| Contents..... | 9 |
| 1 Introduction | 11 |
| 1.1 The Inquiry’s Terms of Reference..... | 11 |
| 1.2 Structure of the Inquiry | 11 |
| 1.3 Structure of Report..... | 11 |
| 1.4 Field of Expertise | 13 |
| 1.5 Statements | 15 |
| 2 Background | 17 |
| 2.1 The Fire Safety Strategy for High-Rise Buildings | 17 |
| 2.2 The Grenfell Tower Fire Safety strategy..... | 19 |
| 2.3 Assumptions Embedded in the Grenfell Tower Fire Safety Strategy | 22 |
| 2.4 Differentiating “Adequate” from “No” FIRE Spread..... | 25 |
| 2.5 Key Stages of the Timeline | 29 |
| 3 Stage One: Breaching of the Compartment..... | 30 |
| 3.1 Introduction..... | 30 |
| 3.2 The Fire Compartment | 31 |
| 3.2.1 Ventilation Sources | 32 |
| 3.2.2 Fuel Sources | 32 |
| 3.3 Timeline of The Kitchen Fire | 34 |
| 3.4 Bounding the Compartment Fire..... | 35 |
| 3.4.1 Material Properties | 35 |
| 3.4.2 Fire Size and Compartment Temperature..... | 36 |
| 3.4.3 Estimation of Fire Base Area | 39 |
| 3.4.4 Thermal Performance of the uPVC Window Surround..... | 39 |
| 3.5 Mechanisms of Ignition of an external flame..... | 44 |
| 3.5.1 Ignition by Direct Impingement | 47 |
| 3.5.2 Fires Behind an Obstacle..... | 50 |
| 3.5.3 The Fan and Fan Mounting Unit as an Ignition Source of the ACP | 51 |
| 3.6 Relevant Active and Passive Fire Safety Systems | 52 |
| 3.7 Summary..... | 52 |

| | | |
|---------|--|-----|
| 4 | Stage Two: Vertical Fire Spread | 55 |
| 4.1 | Vertical Fire Spread at Grenfell Tower | 55 |
| 4.2 | Vertical Fire Spread Over ACP Panels | 56 |
| 4.3 | Controlling Mechanisms of Flame spread | 62 |
| 4.4 | Effect on Tenability and Structural Stability | 64 |
| 4.5 | Compliance Issues Affecting the Characteristics of Stage Two | 65 |
| 4.6 | Understanding the Relationship Between Compliance, Performance and Quality | 66 |
| 4.7 | Summary | 68 |
| 5 | Stage Three: Lateral Fire Spread and Internal Migration | 70 |
| 5.1 | Lateral Migration of the External Fire | 70 |
| 5.1.1 | Mechanisms Driving Lateral Flame Spread | 70 |
| 5.1.2 | Detailed Analysis of the External Spread of the Fire | 75 |
| 5.2 | Internal Penetration | 77 |
| 5.2.1 | Glazing Failure | 78 |
| 5.2.2 | Kitchen Extraction Fan Failure | 79 |
| 5.2.3 | Internal Penetration Summary | 85 |
| 5.3 | Fire and Smoke Migration to the Interior | 85 |
| 5.3.1 | Early Passage of Smoke Through the Building | 87 |
| 5.3.2 | Compartmentalization Performance Following Fire Re-entry | 89 |
| 5.3.2.1 | The Contribution of the Re-entrant Fire | 90 |
| 5.3.2.2 | Failure of Flat Doors | 96 |
| 5.3.2.3 | Mechanisms for Internal Smoke Spread | 99 |
| 5.3.3 | Internal Smoke Spread | 105 |
| 5.3.4 | Onset of General Untenable Conditions | 113 |
| 5.3.4.1 | Interpretation | 114 |
| 5.4 | Assessment of Characteristic Structural Heating During Stage Three | 115 |
| 5.5 | Compliance Issues Affecting the Characteristics of Stage Three | 116 |
| 5.6 | Summary | 117 |
| 6 | Stage Four: Untenable Conditions in the Building | 119 |
| 6.1 | Location of Casualties | 119 |
| 6.2 | Post-Fire Structural Assessment | 121 |
| 6.3 | Summary | 126 |
| 7 | Conclusions | 128 |
| 8 | References | 130 |

252 1 INTRODUCTION

253 1.1 THE INQUIRY'S TERMS OF REFERENCE

254 The Inquiry's Terms of Reference have been approved by the Prime Minister and have been published
255 on the Inquiry's website. The Inquiry has also published on its website a detailed provisional List of
256 Issues which identify the matters with which its investigation will be concerned. This provisional List
257 may be revised in due course.

258 1.2 STRUCTURE OF THE INQUIRY

259 The Chairman has indicated that Inquiry will be conducted in two phases.

260 Phase 1 of the Inquiry is intended to investigate the development of the fire itself, where and how it
261 started, how it spread from its original seat to other parts of the building and the chain of events that
262 unfolded during the course of the hours until it was finally extinguished. Phase 1 is also examining the
263 response of the emergency services and the evacuation of residents. The Chairman has noted that it
264 is necessary to address these questions first for two reasons:

- 265 1. there is an urgent need to identify what aspects of the building's design and construction
266 played a significant role in enabling the disaster to occur; and
- 267 2. until the chain of events is understood, it will not be possible to pinpoint the critical
268 decisions that had a bearing on the fire.

269 The Chairman asked me to provide a report for Phase 1 on:

- 270 (a) The ignition of the Grenfell Tower façade materials.
- 271 (b) Fire spread to and on the exterior of Grenfell Tower.
- 272 (c) Fire and smoke spread within Grenfell Tower.

273 The current document is my Phase 1 Report.

274 1.3 STRUCTURE OF REPORT

275 The report will be structured around a series of general topics that attempt to describe how a high-
276 rise residential building should have responded to a single fire event (Fire Safety Strategy). A fire is a
277 chemical reaction governed by Newtonian physics, therefore its behaviour can be described in terms
278 that are consistent with this framework. In a similar manner, the response of a building to the fire can
279 be described using basic and well accepted scientific principles. The report will first present the fire
280 safety strategy in these terms. It is clear that the complexity of the interactions is very significant,
281 therefore the description of the different processes will remain general and simplified. It is accepted
282 that the general presentation will not cover some of the important details. These will be left for later
283 sections.

284

285 Building Regulations provide structured approaches that address the progression of a fire and its
 286 interactions with a building. Building Regulations accept that a single fire event will occur in a building.
 287 Then, the objective of Building Regulations is to manage this fire event in a manner such that the
 288 consequences are acceptable to society. For that purpose, Building Regulations invoke engineering
 289 tools and engineered systems as well as reference to the fire brigades. The interaction between the
 290 building, the engineered systems and the fire brigades with the fire are governed by the laws of physics
 291 and in principle could be describable by means of engineered tools. Nevertheless, the complexity of
 292 some of these interactions is such that sometimes the implemented solutions have to be sufficiently
 293 over-dimensioned (or robust) to provide confidence of adequate performance without the explicit
 294 representation of the physics. Building Regulations are, in principle, meant to provide these robust
 295 solutions that meet the objectives of the fire safety strategy. Some Building Regulations approach
 296 these solutions as functional requirements others as detailed sets of rules.

297 An analysis of Building Regulations and their manifestation in building design is beyond the scope of
 298 this report, nevertheless, this report will include references to particular Building Regulations that aim
 299 to address each aspect of the fire safety strategy applied to Grenfell Tower. Examples of these Building
 300 Regulations will be extracted from Mr Todd's report [1] to serve as illustration of how those Building
 301 Regulations provide solutions to the requirements of the fire safety strategy.

302 The events of June 14th, 2017 will be discussed following the structure described below:

- 303 1. Assessment of the evolution of the fire within the room of origin. The room of origin is
 304 assumed to be the kitchen of Flat 16 based on references [2] and [3]. An analysis of the
 305 potential dynamics of the fire event will be used to provide some insight into the mechanisms
 306 by which the fire exited the compartment of origin. These mechanisms will be contrasted
 307 against the fire safety strategy and compliance failures as per reference [4].
- 308 2. Assessment of the external fire growth and its impact on tenability¹¹. Details of the evolution
 309 of the external fire will be extracted from reference [5] together with video, photographs and
 310 other documentation provided by the Public Inquiry. These will be used to describe the time
 311 evolution of tenability through the building.
- 312 3. Comparison with prior events. The evolution of the Grenfell Tower fire will be contrasted with
 313 past fire events with similar characteristics and where there were similar compliance failures
 314 as per reference [4]. This information will be used to provide some insight into aspects of the
 315 fire safety strategy that were critical to the outcome.

316 The description of human behaviour in the event of a fire requires more than a Newtonian physics
 317 framework. A fire safety strategy is intended to provide sufficiently robust solutions that do not
 318 depend upon a detailed analysis of human behaviour. The interactions between people and the fire,
 319 human behaviour and decision making will therefore not be discussed in this report. In contrast, the
 320 evolution of the fire as it pertains to tenability of the different areas of the building will be discussed
 321 in detail. Placement and communications from individuals within the building will be contrasted with

¹¹ See footnote (1) for approximate times for each stage.

322 the evolution of the fire to draw conclusions on the impact that each element of the fire safety strategy
323 had on the evolution of tenability.

324 The intervention timeline and firefighting procedures are beyond the scope of this report, but
325 nevertheless, the evolution of firefighting activities relative to the fire growth and the attainment of
326 untenable conditions will be discussed. The evolution of the fire will be contrasted with fire brigade
327 related information to draw conclusions on the role of each element of the fire safety strategy.

328 1.4 FIELD OF EXPERTISE

329 1.4.1. My name is José L. Torero. I am the John L. Bryan Chair at the Department of Fire Protection
330 Engineering and the Director of the Center for Disaster Resilience at the Department of Civil
331 Engineering at the University of Maryland, USA. I also serve as Director of TÆC. Previously, I was Prof.
332 of Civil Engineering and Head of the School of Civil Engineering at the University of Queensland,
333 Australia (2012-2017). Before moving to Australia, I held the Landolt & Cia Chair for
334 Innovation for a Sustainable Future at the Ecole Polytechnique Fédéral de Lausanne, Switzerland
335 (2012) and the BRE Trust/RAEng Chair in Fire Safety Engineering at the University of Edinburgh
336 (2004-2011). Between 2004 and 2011 I was also the Director of the BRE Centre for Fire Safety
337 Engineering and in the 2008 to 2011 period I was Head of the Institute for Infrastructure and
338 Environment, both at the University of Edinburgh. I have held other positions at CNRS (France),
339 University of Maryland (USA), NIST (USA) and NASA (USA).

340 1.4.2. My field of expertise is fire safety; a field in which I have worked for more than 25 years. I was
341 trained as a Mechanical Engineer obtaining a Bachelor of Science from the Pontificia Universidad
342 Católica del Perú in 1989. In 1991 I obtained a Master of Science and in 1992 a PhD from the University
343 of California, Berkeley, both in Mechanical Engineering with specialty in Fire Safety. I am a Chartered
344 Engineer by the Engineering Council Division of the Institution of Fire Engineers (UK), a Registered
345 Professional Engineer in Queensland and a full member of the Society of Fire Protection Engineers
346 (USA).

347 1.4.3. I am a Fellow of the Royal Academy of Engineering, the Royal Society of Edinburgh, the
348 Australian Academy of Technological Sciences and Engineering, The Institution of Civil Engineers, The
349 Institution of Fire Engineers, the Society of Fire Protection Engineers and the Combustion Institute. In
350 2008 I was awarded the Arthur B. Guise Medal by the Society of Fire Protection Engineers (USA)
351 and in 2011 the David Rasbash Medal by the Institution of Fire Engineers (UK) in recognition for
352 eminent achievement in the education, engineering and science of fire safety. In 2016 I was
353 awarded a Doctor of Science *Honoris Causa* from Ghent University, Belgium. I
354 am the author of more than 500 technical documents in all aspects of fire safety of which more than
355 200 are peer review scientific journal publications. I have been invited to deliver more than 100
356 keynote lectures in conferences and professional fora worldwide of which more than 20 have been
357 in the area of Fire Investigation.

358 1.4.4. I was the Editor-in-Chief of Fire Safety Journal (2010-2016), the most respected scientific
359 publication in the field, Associate Editor of Combustion Science and Technology (1997-2008) and a
360 member of the Editorial Board of Fire Technology, ICE Journal of Forensic Engineering, Fire Science
361 and Technology, Case Studies in Fire Safety, Progress in Energy and Combustion Science and the

Journal of the International Council for Tall Buildings. I am one of the Editors of the 4th Edition of the Fire Protection Engineering Handbook of the Society of Fire Protection Engineers (USA) and an author of several chapters. I am regularly in the Scientific Advisory Boards of most conferences in the field and a member of the Committee of many professional organizations. I chaired the Fire Safety Working Group for the International Council for Tall Buildings and Urban Habitat and was the vice-Chair of the International Association for Fire Safety Science.

1.4.5. I have been involved in numerous fire investigations many of which have been landmark studies. Between 2001-2010 I was involved in an independent investigation of the World Trade Center buildings 1 and 2 collapses. I was involved in the fire and structural modelling of the World Trade Center building 7 collapse in support of litigation and conducted an independent investigation of the fire growth and structural failure of the Madrid Windsor Tower Fire commissioned by the British Concrete Institute. I conducted a cause and origin investigation of the Texas City explosion and subsequent fires as well as a damage correlation analysis. I conducted dispersion fire modelling supporting the litigation of the Buncefield Explosion and of the Sego mine explosion (USA). I supported the fire service investigation of the Ycua Bolanos supermarket fire in Paraguay to establish the cause of the fire and to analyse the reasons for the fatalities. I conducted the fire investigation of La Rocha prison fire in Uruguay where 12 inmates died where we developed analytical and numerical model of fire growth in support of the investigation. I conducted the fire investigation of the San Miguel prison fire in Chile where 26 inmates died where we developed analytical and numerical models of fire growth in support of the investigation. I worked with the Scottish Fire Service on the Balmoral Bar fire investigation. I conducted the post-fire structural assessment of the Abu-Dhabi Plaza fire in Kazakhstan, probably the biggest ever fire of a building under construction. Recently, I led the fire investigation of the Ayotzinapa 43 murder case driven by the Organization of American States that encouraged the Mexican government to reopen the investigation. (*Science*, 11 March 2016, vol. 351 Issue 6278, pp.1141-1143 and *Science*, 29 April 2016, vol. 352, issue 6285, p.499) and by the National Academy of Science (USA) (<http://www7.nationalacademies.org/humanrights/>). I served as advisor to the Attorney General of Mexico in the subsequent investigation. I have given expert testimony in several forensic fire investigations worldwide.

1.4.6. I have developed novel methodologies for forensic fire investigation that have affected the manner in which fire investigation is conducted and its legal ramifications (V. Brannigan and J. L. Torero, "The Expert's New Clothes: Arson "Science" After Kumho Tire," *Fire Chief Magazine*, 60-65, July 1999.). For these studies I have received the William M. Carey Award for the Best Paper Presented at the Fire Suppression and Detection Research Application Symposium (C. Worrell, G. Gaines, R. Roby, L. Streit and J.L. Torero, "Enhanced Deposition, Acoustic Agglomeration and Chladni Figures in Smoke Detectors," *Fire Technology*, Fourth Quarter, 37, Number 4, pages 343-363, 2001), the Harry C. Bigglestone Award for the Best Paper Published in *Fire Technology* (T. Ma, S.M. Olenick, M.S. Klassen, R.J. Roby and J.L. Torero, "Burning Rate of Liquid Fuel on Carpet (Porous Media)" *Fire Technology*, 40,3, 227-246, 2004) and the Telford Premium Best Paper Award by the Institution of Civil Engineers (J.L. Torero, "Forensic Analysis of Fire Induced Structural Failure: The World Trade Centre, New York" *ICE Journal of Forensic Engineering*, 164, 2, 69-77, 2011.). I was awarded the FM Global Best Paper Award for a paper on the precision of fire models and the required skills for fire modelling (G. Rein, J. L. Torero, W. Jahn, J. Stern-Gottfried, N. L. Ryder, S. Desanghere, M Lazaro, F. Mowrer, A. Coles, D. Joyeux, D. Alvear, J. A. Capote, A. Jowsey, C. Abecassis-Empis,

405 P. Reszka, Round-robin study of a priori modelling predictions of the Dalmarnock Fire Test One, Fire
406 Safety Journal, 44, 590-602, 2009.).

407 1.4.7. For more than 20 years I have been involved in the education and training of fire engineers,
408 fire investigators and the fire service. I have developed training programmes on fire investigation for
409 the Bureau of Alcohol Tobacco and Fire Arms (USA), fire investigators and fire brigades in the UK
410 (University of Edinburgh short course in Fire Science and Fire Investigation, 2001-20012), the RAIB
411 (UK) and the Police Scientifique of Lyon (France) among others. I have taught courses at Fire Service
412 College Gullane, for the Queensland Fire and Emergency Services and for the fire services in
413 numerous other countries (Costa Rica, Chile, Peru, Argentina, Singapore, Malaysia, etc.). I have
414 developed curriculum and taught the Fire Protection Engineering programme at the University of
415 Maryland, the Structural and Fire Safety Engineering course at the University of Edinburgh, the Civil
416 and Fire Safety Engineering course at the University of Queensland and the International Masters
417 in Fire Safety Engineering (Ghent, Lund and Edinburgh Universities). I was external examiner to the
418 Fire Safety programme of Glasgow Caledonian University (UK) and I am on the Advisory Board of
419 Worcester Polytechnic Institute (USA) Fire Protection Engineering programme. I am a Distinguished
420 Visiting Chair Prof. in Fire Safety Engineering at the Hong Kong Polytechnic University.

421 1.4.8. In the period 2007 to 2010 I lead the development of the FireGrid project funded by the
422 Department of Trade and Industry and in partnership with the London, Manchester, Strathclyde and
423 Lothian and Borders Fire Brigades where a detailed study of the role of information on fire brigade
424 emergency response was analysed. This project was featured in the 2007 BBC Horizon Documentary
425 "Skyscrapers Fire Fighters" that has been shown in more than 30 countries. In 2010 I was awarded a
426 GBP 2M grant by the Engineering and Physical Sciences Research Council UK to study the Real Fires
427 for the Safe Design of Tall Buildings.

428 1.4.9. I have been involved in numerous advisory roles for industry and government many of them
429 including the fire service. I was involved in the Nuclear Regulatory Commission (USA), PRIT
430 Committee on Fire Modelling, a member of the Expert panel of the Fire and Resilience Directorate
431 (Communities and Local Government, UK) and of the Forum of Chief Fire Officers of Scotland (SDAF).
432 I was advisor to the Department of Transportation and Main Roads (Queensland, Australia), special
433 advisor to the vice- President of Peru on the Utopia Club and Mesa Redonda fire investigations and
434 a member of the CFOA Training Needs Analysis Gateway Review Group. I am currently special advisor
435 to the Minister of Housing (Queensland) on issues of façade fires. I am a regular participant in
436 standards development committees worldwide.

437 1.4.10 A full and up to date CV (current at the time of Torero's initial instruction as Expert Witness)
438 has previously been provided to the Inquiry's Core Participants.

439 1.5 STATEMENTS

440 *I confirm that I have made clear which facts and matters referred to in this report are within my own*
441 *knowledge and which are not. Those that are within my own knowledge I confirm to be true. The*
442 *opinions I have expressed represent my true and complete professional opinions on the matters to*
443 *which they refer.*

444 *I was assisted in the production of this report by the following individuals:*

445 *Dr Adam Cowlard - Director and senior engineer at Torero, Abecassis Empis and Cowlard Ltd. Dr*
446 *Cowlard holds a PhD in Fire Safety Engineering and an MEng in Civil Engineering from the University*
447 *of Edinburgh. He has undertaken a wide range of consultancy and research work encompassing*
448 *development of fire safety strategies for a wide range of complex infrastructure, development of*
449 *design fires and heat transfer modelling, and fire and evacuation modelling. Dr Cowlard supported my*
450 *work primarily on modelling, data analysis, reporting and reviewing.*

451 *Dr Richard Krupar III – While conducting this work he was a post-doctoral research associate at the*
452 *Center for Disaster resilience at the University of Maryland. Dr Krupar holds a PhD in Wind Science and*
453 *Engineering and is an expert in damage assessment. He has conducted damage assessment for many*
454 *major events such as Hurricane Harvey. Dr Krupar supported my work primarily on the damage*
455 *analysis, video footage assessment, reporting and reviewing.*

456 *Mr Alex Duffy – Faculty Assistant at the Department of Civil Engineering (University of Maryland. Mr*
457 *Duffy holds a Master in Design Studies from Harvard Graduate School of Design, and a Master in Civil*
458 *Engineering from the University of Edinburgh. He has more than five years' experience in fire safety*
459 *engineering design. Mr Duffy supported my work primarily through data collection, analysis,*
460 *organization of information, reporting and reviewing.*

461 *I confirm that I understand my duty to assist the Inquiry on matters within my expertise, and that I*
462 *have complied with that duty. I also confirm that I am aware of the requirements of Part 35 and the*
463 *supporting Practice Direction and the Guidance for the Instruction of Experts in Civil Claims 2014.*

464 *I confirm that I have no conflict of interest of any kind, other than any which I have already set out in*
465 *this report. I do not consider that any interest which I have disclosed affects my suitability to give*
466 *expert evidence to the Inquiry on any issue on which I have given evidence and I will advise the Inquiry*
467 *if, between the date of this report and the Inquiry hearings, there is any change in circumstances which*
468 *affects this statement.*



469 Signed:

Dated: 23 May, 2018

470 2 BACKGROUND

471 2.1 THE FIRE SAFETY STRATEGY FOR HIGH-RISE BUILDINGS

472 To guarantee the safety of people occupying a high-rise building during a fire event, it is necessary to
473 implement a complex and precise fire safety strategy [7, 8]. The components of such a fire safety
474 strategy can be explicitly stated or introduced in an implicit manner through prescriptive
475 requirements. In both cases, the design of such a strategy requires careful consideration because the
476 safe use of a high-rise building is a complex problem [7, 8].

477 Fire safety strategy, as referred to in this document, is the concept by which different measures are
478 taken to guarantee a societally accepted adequate level of safety of people against fire. It is also
479 implied that by guaranteeing the adequate safety of people, material losses will also be mitigated. In
480 many countries, the concept of a fire safety strategy is required to be translated to documents that
481 are part of the approvals process and might be referred by the same name or others (e.g. Fire safety
482 brief, fire protection strategy, fire engineering brief, etc.). For the purpose of this report the term fire
483 safety strategy is not related to any of these documents but remains purely as the concept explained
484 above.

485 The fire safety strategy is linked to how the building is defined or classified. The definition of a building
486 that is to be classified as a high-rise building is also complex. Regulations many times propose simple
487 definitions of a high-rise building only on the basis of height, (Sections 4.1.5 and 4.1.6 [1]) nevertheless
488 numerous assumptions hide behind the classification. These assumptions, together with the many
489 protective measures implemented, allow these buildings to be used in a safe manner. The
490 assumptions and protective measures will vary depending on the specific characteristics and use of a
491 building (Section 4.1.6 [1]).

492 Conceptually, the fire safety strategy for a high-rise building recognises that the main characteristic
493 that defines a high-rise building is a convergence of time scales. In a high-rise building, people will take
494 significant time to evacuate (several minutes), therefore the time to egress is of the same order of
495 magnitude as the time for failure or the time required for fire and rescue service intervention [8]. Time
496 for failure could be defined in many ways, such as attainment of conditions that are untenable,
497 structural failure, etc. In buildings that are not classified as high-rise, egress times are generally very
498 short compared to all other characteristic times, therefore occupants are not expected to interact
499 with firefighting operations or with the different potential modes of failure. It is clear that this will
500 only be the case if the fire safety strategy works appropriately during the fire event.

501 Given this convergence of time scales, there is insufficient time to evacuate everyone and therefore a
502 high-rise building requires the existence of safe areas within the building. These safe areas are
503 intended to assure the wellbeing of occupants while the fire grows and while countermeasures and
504 fire fighter operations are in progress. Furthermore, in the case of vulnerable people, these safe areas
505 will serve to provide protection until rescue is achieved (Section 2.105 [1]).

506 The most common safe areas are the stairwells. Stairwells are intended to remain isolated from the
507 event during the duration of the fire, guaranteeing the egress process. There is no limit to the time
508 where stairwells are to remain safe. To maintain the stairs as safe areas during the fire, these have to

509 be constructed such that the fire is prevented from damaging the enclosure (i.e. walls and doors).
 510 Furthermore, redundancies are necessary for all safety systems; therefore, supplemental protection
 511 can be introduced to prevent smoke from entering the stairs. Typical approaches are: ventilated
 512 lobbies that create a buffer between areas with combustible materials and the stairs, or increasing
 513 the pressure within the stair thus ensuring a flow of air from the stair to the lobby (as opposed to
 514 smoke from the lobby to the stair), etc. Some of these are discussed in Section 3.2.20 of Dr. Lane's
 515 Phase One report [4].

516 Also, it is important for safety systems to have redundancies, therefore having more than one means
 517 of egress is highly desirable. Nevertheless, it is recognised that emergency stairs can occupy a
 518 significant fraction of the surface area of a high-rise building, challenging its functionality. Limiting the
 519 number of stairs therefore might be necessary. In this case, other forms of redundancy might be
 520 introduced. A common form of redundancy is to prevent the fire or smoke from escaping the sector
 521 of the building where the fire originated. This is achieved by means of barriers that block the
 522 progression of a fire out of a sector. Egress, in this case, can be contained to the high-risk sectors of
 523 the building and the rest of the occupants will remain in place. All other sectors of the building are
 524 deemed safe. Firefighting operations will proceed with occupants in the building, therefore, provisions
 525 have to be made to account for firefighter-occupant interactions. These provisions are in part
 526 designed into the building but also relate to firefighting operations. This strategy is generally named
 527 "stay put" or "defend-in-place."¹²

528 Buildings will bound these sectors by means of barriers that are qualified as "fire resistant"¹³. Typically,
 529 for residential units, each unit represents a sector, therefore the perimeter of the unit needs to meet
 530 "fire resistance" requirements. Certain boundaries of the sector can be deemed more important than

¹² The term "stay put" is common in the UK and it is directed towards the occupants and the instructions that need to be provided to them so that their actions during a fire are consistent with the fire safety strategy [1]. The term "defend in place" is more common in North America and emphasizes firefighting operations. The term "defend in place" indicates that firefighters will be aware that occupants will remain in place while firefighting operations proceed. While both terms might represent slightly different procedures, the primary intention is the same for "stay put" and "defend in place" strategies. In both cases, rescue (i.e. firefighter managed egress) and firefighting operations supersede occupant driven egress. These definitions are not identical but consistent with those presented in Dr. Lane's Phase 1 Expert Report (Sections 2.8.7 and 2.8.20 [4]).

¹³ Fire resistance is a standard term used to describe the performance of structural components in a standard test. This test is recognized internationally (BS 476, ISO 834, ASTM-E 119, etc.) and it provides a standard and severe thermal exposure to the structural element by means of a furnace. The structural element is introduced in the furnace and the furnace temperature is then increased in a predefined and standard manner. The term "fire resistance" is then defined as the time (in intervals of 30 minutes) that the structural element can withstand the thermal exposure before it reaches a predefined failure criterion (normally specified as a critical temperature). It is important to clarify that the standard thermal exposure does not correspond to a typical thermal exposure during a fire and structural elements do not behave in exactly the same manner in a furnace as in a building, therefore the "fire resistance" does not represent a real time to failure. "Fire resistance" is nevertheless considered as a "worst case scenario" that provides a relative ranking between structural elements. Structural elements that are to act as barriers (floors, walls, doors, etc.) will therefore have to meet requirements of "fire resistance" before they can be used in a building. Products such as doors, fire-stop systems, etc. will be tested and listed with a "fire resistance" before they can be sold as barriers. Commonly used structural elements such as partition walls will be designed and built in a manner consistent with systems that have been tested and certified. Some variations can be permitted but, in general, given the complexity of these systems, any variation will have to be analyzed and approved by a competent professional.

others, therefore a higher “fire resistance” might be required. It is typical to recognize that global structural integrity and containment of a fire to the floor of origin are of critical importance for high-rise buildings, therefore floor slabs and main structural elements generally will have higher fire resistance requirements than doors or non-load bearing partition walls.

It is recognized that certain components of these sectors cannot behave as barriers to the same extent as walls or floor slabs. Windows are some of these necessary components. Windows will incorporate glazing and could be potentially open, nevertheless, provisions are still necessary to prevent a fire from entering the adjacent sectors. Figure 1 shows an external photograph of the recent Trump Tower fire in New York (April 8th, 2018). Figure 1(a) shows the magnitude of the fire and Figure 1(b) the external glazing after the event. The figure shows that the fires did not progress to the sectors above or adjacent to the sector of fire origin. In this case the compartmentalization¹⁴ provisions performed adequately. Unfortunately, a detailed investigation is currently unavailable and therefore the design features that enabled the adequate behaviour of this building cannot be established.



FIGURE 1: TRUMP TOWER FIRE, APRIL 8TH, 2018 (A) THE FIRE DURING BURNING SHOWING A FULLY DEVELOPED POST-FLASHOVER FIRE (B) THE AFTERMATH SHOWING THE EXTENT OF DAMAGE OF THE GLAZING.

It is important to note that robustness and redundancies are paramount for high-rise buildings because for these buildings the evolution of a fire, as it scales-up, can be extremely complex [9] and the behaviour of occupants over such long time-scales is highly uncertain. Furthermore, the performance of many of the fire safety systems and that of the fire brigades is stretched [8]. Given the characteristics of high-rise buildings, Building Regulations will therefore stipulate robust solutions and many redundancies [1].

2.2 THE GRENFELL TOWER FIRE SAFETY STRATEGY

The Grenfell Tower was classified as a high-rise residential building due to its height and occupancy. As such a fire safety strategy that is consistent with this classification would have been implemented. This section explores the different fire safety measures observed in Grenfell Tower and structures them in the context of a conceptual fire safety strategy. This section does not analyse any document on the matter of the fire safety strategy that could have been written for approvals or other purposes.

¹⁴ Compartmentalization is the term used to describe the concept of delivering a sector that is expected to fully contain a fire. The sector is therefore generally termed a compartment. A compartment is protected by fire resistant barriers and is designed to prevent a fire from spreading to any adjacent compartment.

559 The building had limited means of egress (one stair) and therefore required a “stay put” strategy. In
560 conceptual terms the safety of occupants in such a high-rise situation would be guaranteed in the
561 following general ways:

- 562 • The objective of a fire safety strategy is to mitigate the consequences of a fire. Therefore, a
563 fire is assumed to occur. Arson and premeditated fires are not contemplated in Building
564 Regulations and therefore the assumption is that there will be a single event. Lobbies and
565 stairs are required to be free of combustible materials so, in a building of this nature, fires are
566 assumed to start and remain within a residential unit. The residential unit represents the
567 sector to be enclosed by “fire resistant” barriers.
- 568 • Maximum allowable travel distances within the unit are restricted and smoke/heat detection
569 and alarm is required (Section 1.5 [1]). Adequate detection and alarm will rapidly start the
570 onset of egress, and the short travel distances will guarantee that occupants of the residential
571 unit where the fire originates will reach a safe area before conditions within the residential
572 unit are untenable.
- 573 • Sprinklers can be used as a means to control the rate of growth of a fire, giving the tenant
574 more time to exit the unit. Whilst sprinklers can potentially extinguish the fire of origin, thus
575 eliminating the problem, responsible design cannot assume that, due to the presence of
576 sprinklers, a fire event that challenges the lives of tenants will not occur. Sprinklers will only
577 reduce the probability of a life-threatening fire and therefore can be included as
578 supplemental protection, but do not supersede other elements of the strategy (Section 2.30
579 [1]). In the case of Grenfell Tower it was not required to have sprinklers [1] as supplemental
580 protection given the time that it was built and sprinkler protection was therefore not
581 incorporated.
- 582 • Detection and alarm systems within a residential unit are not interconnected to the rest of
583 the building. Interconnected detection systems are not generally desirable because
584 otherwise a minor event can lead to the unnecessary evacuation of a building. Instead, the
585 residential unit is the sector that is enclosed (walls, floor and ceiling) such that the fire/smoke
586 cannot escape the unit until the full burn-out¹⁵ of all combustible materials (fire resistant
587 compartmentalization). A detection/alarm system that is interconnected to the rest of the
588 building could then be placed in the lobby outside the residential unit. If the smoke has
589 breached the barrier and compromised the lobby an alarm will occur. This signals the onset
590 of egress for all floors at risk. It is possible to adopt an alternative approach. For example, it
591 is possible to have a detection system in the lobby which will activate and provide a means
592 by which egress paths can be kept clear of smoke, allowing for safe evacuation of the
593 occupants if necessary (Section 1.5 [1]). In the Grenfell Tower the smoke detector in the lobby
594 was not required to be interconnected (Section 1.5 [1]) but was introduced as part of the
595 smoke control system whose objective was to maintain egress paths clear from smoke.
- 596 • To deliver the enclosure of the residential unit, walls, ceilings and floors are designed in a
597 manner that they prevent fire and smoke from penetrating throughout the duration of
598 burning. This applies to all penetrations (electrical, water, sewage, mechanical, gas, etc.) as
599 well as doors. Doors designed to withstand a fire as well as self-closing systems are generally

¹⁵ Design for burn-out is a concept implicit in the definition of required fire resistance. Structural components should be capable of withstanding the heat generated by a fire until all the fuel has been consumed. Therefore, the energy delivered by a fire until burnout should be less than the energy delivered by the fire resistance furnace until the time associated to the required fire resistance. Other factors can enhance the required fire resistance such as safety factors that serve as multipliers used to manage situations with different levels of risk.

required to prevent smoke from escaping the residential unit (Section 2.4 [1]). The requirements of all these barriers are expressed in terms of “fire resistance.”

- An unavoidable penetration of the residential unit are the widows and other outward facing openings (e.g. extraction systems). These penetrations need to be designed in a manner that prevents a fire from entering any of the areas adjacent to the residential unit. It is recognized that glazing will either be open or fail in the event of a fire, therefore spreading to adjacent spaces is controlled by carefully defined strategies. Simple systems will rely on geometrical constraints that do not allow flame projections to enter adjacent spaces; more complex systems require more intricate solutions. The original design of Grenfell Tower achieved these objectives by means of simple geometrical constraints imposed on the external geometry and non-combustible fabric of the building. The refurbished building included an attached cladding system that required a more complex approach to the problem that included cavity barriers as well as detailed flammability assessment requirements for the systems used. It is important to note that the objective is to prevent a fire or smoke generated in a residential unit from penetrating any of the adjacent spaces (Section 2.24 [1]).
- In a similar manner, all vertical pathways need to be protected to prevent smoke and fire from progressing internally through the building beyond the residential unit of origin. Vertical pathways will include services, lifts, etc.
- In the event of a fire, occupants within the residential units at risk will proceed to evacuate immediately. The lobby is expected not to contain any combustible materials and to be separated from all combustibles by a barrier (Section 2.95 [1]). These barriers can be properly designed walls, enclosures or doors (Section 1.4 [1]). The units at risk could be interpreted as those in the floor of the fire or even just the unit where the fire originated (Section 2.10 [1]).
- The pathway between the residential units and the safe area (i.e. the stairwell) has no redundancy, therefore a smoke management system is used in Grenfell Tower to provide a redundant system that could clear smoke in the event that any of the barriers does not fulfil its function (“smoke dispersal,” Sections 2.7 and 2.8 [1]).
- The occupants might interact with the fire brigades, although such interactions are expected to be in sufficiently small numbers that they will be well structured. Fire brigade predefined procedures will enable adequate interactions (Sections 2.11 to 2.14 [1]).
- Occupants in units that are not deemed at risk will remain in their flats (“stay put”) until instructions are received from the fire brigade. Fire brigade predefined procedures will enable proper management of information to all building occupants (Sections 2.11 to 2.14 [1]).
- Fire brigade operations have the potential to affect the displacement of smoke and flames, therefore, firefighting operations take priority and occupant/fire fighter interactions are expected to be minimized. Fire brigade protocols govern these interactions (Sections 2.11 to 2.14 [1]).
- The building design will consider measures for firefighters to perform their duties adequately (section 2.9 and 2.27 [1]). This includes water supplies, means of access but also all provisions necessary for fire fighters to conduct their duties in a manner that is effective and safe.
- Through the entirety of any firefighting intervention the structure should keep sufficient mechanical strength so that it can fulfil its functions. All structural elements are therefore required to withstand a fire until burn-out. This is normally expressed in terms of “fire resistance” (Section 4.1.16 [1]) and is generally specified not as withstanding burn-out but as “stability will be maintained for a reasonable period” (Section 5.1.14 [1]).

2.3 ASSUMPTIONS EMBEDDED IN THE GRENFELL TOWER FIRE SAFETY STRATEGY

A fire safety strategy relies on many assumptions. Some of these assumptions are associated with the design and implementation process, others with maintenance and many with adequate performance. Having explained the rationale behind the measures implemented or not implemented within the conceptual fire safety strategy for Grenfell Tower it is important to establish some of the key assumptions that enable the performance of these measures:

- That the means to establish performance of all fire safety systems can deliver a performance assessment that is sufficiently accurate and robust. Thus, performance is assumed to be as intended.
- That all components of the fire safety strategy are designed with the intention that they can be built such that the prescribed performance of the design is achieved. The most common means to validate this assumption is through pre-completion inspections and commissioning of the different systems. It is assumed that these occur where necessary.
- That all components of the fire safety strategy are built such that they can be appropriately maintained. Provisions for inspection and maintenance with adequate means to manage repairs and improvements are assumed. It is also assumed that these provisions and means are consistent with the complexity of the systems implemented (Section 2.32 [1]).
- That all professionals involved in the design, building, commissioning, inspection and maintenance have the competency necessary to perform their duties for the specific systems being addressed [10]. Thus, it is possible for the user to rely on the outcome of all professional assessments which have been made (Section 2.32 [1]).

A fundamental performance assumption key to all high-rise buildings is the containment of the fire within the unit of origin. Particularly important is the prevention of vertical flame spread. Horizontal spread to adjacent units is also important albeit I will focus first on vertical flame spread. It has to be noted that the LGA Guide does not envisage “no” external flame spread but states that the external facades of blocks of flats “should not provide potential for extensive fire spread” (Section 2.96 [1]). This will be addressed in detail in the next section.

It is clear that when assessing performance, it is not possible to make absolute statements. Nevertheless, in this particular case, it is important to analyse the implications of vertical flame spread by contrasting that with the scenario of “no” vertical flame spread. If it is assumed that there will be no vertical flame spread then the following performance statements are valid:

1. “Stay put” strategy: If the fire is to be contained to one floor then, in the event of a fire, only the floor of the fire (critical) and the floor above and below need to be evacuated (robustness). The rest of the occupants can remain in the building and wait until the fire service delivers evacuation instructions. Many countries assume the need for a robust approach that requires the evacuation of multiple floors. In the Building Regulations and guidelines applicable to Grenfell Tower there is no requirement for provisions that allow for occupants of more than the flat of fire origin to evacuate (Section 5.1.57 [1]). It is expected that the fire service will control the fire (which might require the use of the stairs) and then establish if there is a need to proceed to evacuate the rest of the occupants. The standard fire service instructions for all occupants away from the immediate floors of the fire will be to remain in place. These

- instructions will only change as a function of a dynamic risk assessment performed by the fire fighter in command (Section 12.25 [1]). But this is only possible if no vertical flame spread occurs. As indicated in Section 5.2.94 [1], this has been acknowledged in 2011 and 2015 versions of BS 9991 where “both versions of the Standard noted that this is (vertical flame spread) particularly important where a “stay put” strategy is in place.”
2. Required Safe Egress Time (RSET): The RSET will be the time for the occupants to reach the stairs if it is possible to consider the stairs as a safe area. The total time for egress of the occupants of the building is no longer a factor of consideration. This is only valid if no vertical flame spread occurs.
 3. Stairs as a Safe Area: Dimensioning of the stairs is calculated to accommodate occupants from a reduced number of residential units and potential firefighting operations (critical). If many floors are evacuated congestion is possible and this has the potential to disable the orderly evacuation process necessary for an emergency. As stated by Colin Todd in his Phase 1 Report. (section 5.1.58 [1]) “...if all residents in a high-rise block chose to evacuate simultaneously, this might well place residents at risk and would create a major impediment for fire-fighting activity by the fire and rescue service.” Adequate fire resistance of walls and doors (critical) and a smoke management strategy for the lobby (robustness) will guarantee the safety of the stairs. The air intake and exhaust systems will be designed on the basis of a single floor fire. But this strategy that makes the stairs a safe space is only applicable if no vertical flame spread occurs.
 4. Detection and Alarm: Detection systems will provide sufficient warning by means of an alarm. Detection systems are only implemented in units and are intended to warn only the occupants of the unit where the fire originates. The fire will not be detected in any other unit. In the absence of adequate conditions for a “stay put” strategy, the detection and alarm system will not deliver adequate warning to the rest of the occupants.
 5. Notification: Instructions that a “stay put” strategy is enabled are not considered necessary and notification is restricted to the unit where the fire originates. Building Regulations and guidelines require no provisions of information to the occupants (Section 9.1.24 (Fire Safety Order Article 13), Section 9.1.26, Section 12.18 [1]). It is not deemed necessary or appropriate to provide detection, alarm or notification in common parts of blocks of flats other than what is required for smoke management. In the absence of mechanisms to provide instructions, and in the event that conditions that nullify the viability of a “stay put” strategy exist (i.e. vertical flame spread), occupants will be left to their own means (and those available to the fire service), to determine that adequate conditions for a “stay put” strategy no longer exist and that an alternative approach is necessary. This is a particularly vulnerable aspect of the approach currently used and supported by Building Regulations and guidelines applicable to Grenfell Tower. If the fire remains within the unit where it originated, this approach remains viable because only those within the unit of origin are in real risk. This is, therefore, only an acceptable approach to public safety or a reasonable requirement for the fire service in the absence of vertical flame spread.
 6. Sprinkler Systems: The design of a sprinkler system enables the control of fires of a magnitude and characteristics consistent with very strict operational requirements. In a residential setting, the design of a sprinkler system serves to control fires that involve furniture and other common materials such as paper, clothing, carpets, etc. The design of the water supply for sprinklers provides sufficient water to control a fire for a limited number of sprinkler heads (normally those that will activate in a one sector/floor fire). If the sprinklers operate in an adequate manner, they will control the fire and eliminate the problem. If the sprinkler is not capable of controlling the fire then the rest of the fire safety strategy has to guarantee the desirable outcome. Therefore, for high-rise buildings, sprinklers are only a supplement to the

fire safety strategy. Their primary purpose is to reduce the probability of a significant compartment fire. The performance of external sprinklers has never been studied with sufficient detail to establish what conditions will result in adequate fire control of external fires. Furthermore, multiple floor fires will exceed the water supply capacity of the sprinkler system. Therefore, a sprinkler system will not provide any protection and is not designed to operate in the event of external flame spread.

7. Structural Performance: The structural system of a high-rise building needs to provide adequate performance during the period where the building still holds occupants or fire fighters. In a “stay put” strategy, an estimation of the time required to fully evacuate the building is difficult. Statistics on the performance of fire fighters in high-rise buildings are not very extensive or quantitative. It is therefore preferable to design a high-rise building to withstand burn-out of the fuel load. The implementation of this methodology is normally done by means of fire resistance testing; single-element testing that assumes adequate load redistribution from the areas affected by the fire to areas that remain cold (and thus have their full design strength and stiffness). Horizontal and vertical compartmentalization becomes essential for the fire resistance framework to be valid. Fire resistance can only be a reasonable methodology for structural assessment if no vertical flame spread occurs. It is possible to establish the performance of a structure for different fire sizes in a quantitative manner by using complex analytical methods of structural analysis. Nevertheless, the application of these methods to conditions that involve multiple floor fires is not required or common and was therefore not applied to Grenfell Tower.
8. Firefighting operations: Firefighting protocols for response to high-rise building fires are intimately linked to a single floor fire. Furthermore, for residential buildings, the firefighters should find, upon arrival, a single unit fire. Firefighting provisions, such as water supply, are also dimensioned under the expectation of a certain magnitude event. If vertical flame spread occurs this will require the drastic modification of firefighting protocols and advance planning. These modifications rest within the remit of the command structure of the responding units. As indicated in Section 12.20 [1] of Colin Todd’s Phase 1 Report, “It is the role of the fire and rescue service to make the decision as to whether...evacuation is necessary.” Furthermore, the means by which the fire service can alter the strategy are very basic (by knocking on flat entrance doors, by operating sounders within residents’ flats, etc. (Section 12.20 [1]) and these are all approaches that are inconsistent with a fire that has spread vertically or horizontally.

As is demonstrated from the analysis above, the occurrence of any form of vertical flame spread disables every element of the fire safety assumptions underpinning the Grenfell Tower design.

Horizontal flame spread compromises the adjacent units and has the potential to enhance vertical flame spread. The combined effects of horizontal and vertical flame spread in systems of this scale and complexity has never been studied in any detail. Acceptable rates of flame spread are defined by means of performance scenario testing. The assessment of the validity of these tests is outside the scope of this Phase One report nevertheless should be explored in Phase Two.

In the case of fires progressing inwards, there are no provisions to prevent the inward spread of fires, therefore in the event of vertical or horizontal flame spread there is no structured barrier that will prevent the involvement of further units through fires spreading inwards.

It will however be necessary to examine the active and passive fire safety systems which were in operation at Grenfell Tower at the time of the fire. The Grenfell Tower design incorporated other

layers of fire protection that, in principle, could have enhanced its robustness, even in the event of significant external flame spread. A detailed analysis of the fire performance of this specific building is necessary to establish how the fire penetrated the boundaries of the residential units, resulted in vertical and horizontal flame spread and ultimately disabled all components of the fire safety strategy.

It is important to note that current Building Regulations and firefighting practices will not touch upon a scenario where vertical and horizontal flame spread occurs [1]. Thus, from a regulatory perspective, the assumption of “no” vertical and horizontal flame spread is made. As referred to in Section 9.2.35 (v.) of Colin Todd’s Phase 1 Report [1], the LGA Guide indicates that “The “stay put” principle is undoubtedly successful in an overwhelming number of fires in blocks of flats. In 2009-2010, of over 8,000 fires in blocks of flats, only 22 fires necessitated evacuation of more than five people by the fire and rescue service.” While the statistics support the “stay put” approach, there is no indication of the relationship between its success and the success of compartmentalization. Furthermore, there is no indication of the conditions of the fires in the 22 cases that necessitated the evacuation of more than five people. This lack of detail further emphasizes the assumption that “no” vertical and horizontal flame spread will occur and that there is no need for further analysis of the relationship between the success of compartmentalization and success of the “stay put” strategy.

An implicit difficulty with the Building Regulations is the acceptance of some level of fire spread, by referring to the concept of “adequate” fire spread. This will be discussed in more detail in the following section.

2.4 DIFFERENTIATING “ADEQUATE” FROM “NO” FIRE SPREAD

It is clear from Section 2.3 that all Building Regulations and firefighting practices relevant to Grenfell Tower do not touch upon a scenario where vertical and horizontal flame spread occurs [1]. Thus, from a regulatory perspective, the assumption of “no” vertical and horizontal flame spread is implicitly made¹⁶.

Section 12.5 of Approved Document B (ADB) [11] recognizes the hazard associated with external fire spread. It states: “*External Wall Construction. The external envelope of a building should not provide a medium for fire spread if it is likely to be a risk to health and safety. The use of combustible materials in the cladding system and extensive cavities may represent such a risk in tall buildings.*” Given the importance of this matter to the fire safety strategy, this issue is one that requires detailed consideration and section 12.5 addresses it in absolute terms.

¹⁶ For the purposes of this report the relationship between the building and the fire will be defined as follows. An internal fire is one that originates and grows within the confines of a compartment in the building. These fires might project flames externally but the fuel is internal to the building compartment. The flame projections deliver heat to the building locally (heat fluxes as high as 120 kW/m² [12]) but unless they ignite materials placed on the exterior of the building or break into adjacent units, they will not spread because the fuel is all located within the building compartment. Beyond the compartment there will be no fuel to burn. Fires external to the building can be separated in two, external fires fueled by materials on the building envelope and external fires occurring in adjacent buildings. Fires fueled by materials within the building envelope can spread vertically and horizontally and provide heat fluxes similar to those of flame projections from internal fires (up to 120 kW/m²). Fires from adjacent buildings are fueled by materials in a different building and only deliver heat. The magnitude of the heat is assumed not to exceed 12.6 kW/m² (ADB).

815 When the matter is addressed in the functional requirements, the functional requirement B4
816 indicates: "External fire spread: (1) The external walls of the building shall adequately resist the spread
817 of fire over the walls and from one building to another, having regard to height, use and position of
818 the building."

819 The language used in B4 introduces the ambiguity of "adequately" and it also refers to performance
820 in terms such as "resistance." Furthermore, it requires that external walls shall "*resist the spread of*
821 *fire over the walls and from one building to another.*" This leads to many potential interpretations
822 (some of them inadequate) particularly by using the terminology "resist" which suggests that it is
823 related to the concept of "fire resistance."

824 While codes commonly introduce ambiguity to allow for flexibility (which is often necessary for design
825 purposes), in this case it hides a misunderstanding of the significance of vertical and horizontal flame
826 spread to the fire safety strategy. Furthermore, it mixes two fundamentally different issues: fire
827 spreading from another building, with fire initiated within the building and spreading to the external
828 walls. While the latter is introduced in some of the relevant sections, it is clear that fire spreading
829 from adjacent buildings is the main driver of the text.

830 The difference is very significant because in the case of fire spreading from one building to another,
831 the generally accepted approach is to establish that the heat reaching the perimeter wall of an
832 secondary building comes from a single compartment fire within the first building at a defined distance
833 from that wall.

834 When the issue of fire spreading from an adjacent building is quantified, the main assumption in ADB
835 is (Section 13.2): "*a. that the size of the fire will depend on the compartment of the building, so that a*
836 *fire may involve a complete compartment, but will not spread to other compartments.*" Therefore, an
837 explicit requirement for vertical and horizontal compartmentalization is once again introduced. Given
838 a one compartment fire, Section 13.16 of ADB indicates that: "*The aim is to ensure that the building is*
839 *separated from the boundary by at least half the distance at which the total thermal radiation intensity*
840 *received from all unprotected areas in the wall would be 12.6 kW/m² (in still air).*" The value of 12.6
841 kW/m² therefore defines the thermal load expected on external walls (and glazing) for the scenario of
842 fire spreading from an adjacent building. This is of fundamental importance because it defines the
843 requirement that all external components need to meet to prevent fires igniting or entering a
844 compartment from the outside.

845 In the case of a fire initiated within a building (i.e. issued from a compartment fire spill plume) and
846 spreading on an external wall (including arson scenarios such as waste bin fires, etc.), the expected
847 heat fluxes on the external wall can reach values in excess of 120 kW/m² [12]. This is not only an order
848 of magnitude greater in intensity, but it is also a fire whose temporal evolution will be very different.

849 In my opinion, the two scenarios are very different and need to be addressed in an independent way.
850 Nevertheless, ADB does not separate these scenarios. In terms of Guidance and the B4 functional
851 requirement the following is stated:

852 "Performance:

853 In the Secretary of State's view the Requirements of B4 will be met:

- 854 a. If the external walls are constructed so that the risk of ignition from an external source and
 855 the spread of fire over their surfaces, is restricted, by making provision for them to have low
 856 rates of heat release;
- 857 b. If the amount of unprotected area in the side of the building is restricted so as to limit the
 858 amount of thermal radiation that can pass through the wall, taking the distance between the
 859 wall and the boundary into account; and
- 860 c. If the roof is constructed so that the risk of spread of flame and/or fire penetration from an
 861 external fire source is restricted.

862 In each case so as to limit the risk of a fire spreading from the building to a building beyond the
 863 boundary, or vice versa.

864 The extent to which this is necessary is dependent on the use of the building, its distance from the
 865 boundary and, in some cases, its height."

866 It is clear that all sections of Secretary of State's view following and including section (b) are directed
 867 at a fire spreading from an adjacent building and not for the purpose of guaranteeing adequate
 868 performance in the case were the fire initiates within the building. Furthermore, these sections are
 869 not adequate for the scenario were the fire initiates within the building.

870 Section (a) states "*the risk of ignition from an external source and the spread of fire over their surfaces,*
 871 *is restricted, by making provision for them to have low rates of heat release*". This introduces a further
 872 ambiguity through the use of the word "*restricted*." In the case of a 12.6 kW/m² "*external source*"
 873 many materials will not ignite or sustain spread. These include materials listed in Tables A6 (non-
 874 combustible) and A7 (limited combustibility) of ADB. Thus, in that context, the provision is logical.
 875 But, in the case of a 120 kW/m² "*external source*" only completely inert materials such as metals or
 876 ceramics will not ignite or sustain spread (materials classified as non-combustible – Table A6-ADB).
 877 Section (a) also indicates that the "*restriction*" is achieved "*by making provision for them to have low*
 878 *rates of heat release*." When addressing a thermal load of 120 kW/m² on an external wall to achieve
 879 the objective of "*no*" spread, the correct focus should be on the mechanisms controlling the capacity
 880 of a flame to spread. For very high heat fluxes and external walls, the rate of heat release is not the
 881 controlling variable¹⁷ so a provision for a "*low rate of heat release*" is inappropriate.

882 Section 12.7 deals with "*Insulation Material Products*" and states "*In a building with a storey 18 m or*
 883 *more above ground level any insulation product, filler material (not including gaskets, sealants and*
 884 *similar) etc. used in external wall construction should be of limited combustibility (see Appendix A).*"
 885 Many materials that are classified as limited combustibility (e.g. National Class B (Table A7-ADB),
 886 National Class C (table A7-ADB), materials listed in item (5) of Class 0 (Table A8, ADB)) will ignite and
 887 spread a flame when subject to 120 kW/m². So, it is unclear how they will "*adequately resist the spread*
 888 *of fire*."

889 Furthermore, ADB indicates "*External walls should either meet the guidance given in paragraphs 12.6*
 890 *to 12.9 or meet the performance criteria given in BRE Report Fire performance of external thermal*
 891 *insulation for walls of multi storey buildings (BR135) for cladding systems using full scale test data from*
 892 *BS 8414-1:2002 or BS 8414-2:2005.*" But none of that testing contemplates heating from an "*external*

¹⁷ The mechanisms controlling vertical and horizontal flame spread will be discussed in detail in Section 5.

source" of a magnitude of 120 kW/m² [12]. It is necessary to conduct a detailed analysis of BS 8414 aimed at establishing its true relevance and the value of information that can be extracted from the test results. This analysis is beyond the scope of this Phase One report.

Finally, Section 12.1 provides: *"for the external walls to have sufficient fire resistance to prevent fire spread across the relevant boundary."* This is followed by Section 12.2: *"Provisions are also made to restrict the combustibility of external walls of buildings that are less than 1000 mm from the relevant boundary and, irrespective of boundary distance, the external walls of high buildings and those of Assembly and Recreational Purpose Groups. This is in order to reduce the surface's susceptibility to ignition from an external source and to reduce the danger from fire spread up the external face of the building."* All these sections address solely the issue of fires spreading from an adjacent building.

While ambiguity is expected and accepted in functional requirements and guidance, any such ambiguity must nevertheless be compatible with the ability of competent professionals to understand and address any such ambiguity, in a way which means that safe and robust fire strategies can be created.

As I have illustrated above, in the case of external fire spread, the current functional requirements and guidance do not distinguish between external flame spread originating from a fire in an adjacent building from that originating in a room within the building. Given the drastically different characteristics of the thermal input for each scenario, this creates a complex ambiguity that affects classification and performance assessment procedures. The guidance adds to the confusion by not indicating which clauses apply to each scenario and by suggesting performance assessment procedures that might only be applicable to one scenario.

Given the extraordinary importance of external spread to the integrity of the fire safety strategy, I would expect that the ambiguity introduced by these functional requirements and guidance could be easily resolved by competent professional practise. But this is not the case for many materials and in particular for complex assemblies. In my opinion, functional requirements and guidance are not compatible in their current form. The ambiguity associated with performance objectives such as "restricted" and "adequate" is acceptable when addressing external fire spread but the associated performance criteria (e.g. "limited combustibility") and performance terminology (e.g. "resistance") relate to a scenario that is very different (fires providing heat from an adjacent building). In my professional opinion, it is not reasonable to expect professionals, no matter how competent they are, to correct the inconsistencies of functional requirements and guidance.

In the case of Grenfell Tower the combination of materials within the façade system was well known to catastrophically challenge the requirement for "no" external fire spread. A detailed report commissioned by the USA National Fire Protection Association and published in 2014 [13] showed statistics of significant fires with similar assemblies dating prior to 2010. Furthermore, this report explicitly presents several specific cases where similar material combinations had resulted in fires that rapidly compromised many floors and in some cases resulted in fatalities. Thus, façade systems of these nature were an accepted concern worldwide. Thus, whilst I consider the functional requirements and guidance to have been unacceptably unclear, this should not have prevented professionals with a minimum level of competence from establishing that such a system would completely undermine the integrity of the fire safety strategy and therefore provide a medium for fire spread that would definitely pose a risk to health and safety. Given the importance of "no" vertical and horizontal spread, it would have been clear that the occupants of a high-rise building clad by

936 such a façade system would have been at risk and thus a detailed analysis of the impact of vertical and
 937 horizontal flame spread should have been a critical consideration in the design and implementation
 938 of the fire safety strategy.

939 2.5 KEY STAGES OF THE TIMELINE

940 The prior sections provide the general background and considerations that should govern the design
 941 of any high-rise building and the manner in which these background and considerations pertain to
 942 Grenfell Tower. If the fire safety strategy had delivered the intended outcome, an accidental fire
 943 within a residential unit of Grenfell Tower would have remained contained within the unit of fire
 944 origin. Occupants of the unit (and maybe adjacent units) would have evacuated and the fire brigade
 945 would have controlled the event within a matter of minutes. The occupants of all other units would
 946 have stayed put and the building normal operation could have resumed in a matter of hours. The
 947 event, nevertheless, followed a completely different and tragic timeline characterized by the
 948 overwhelming failure of many of the fire safety provisions. It is therefore essential, before drawing
 949 any conclusions, to first study the evolution of this timeline.

950 The following sections provide an assessment of the events of June 14th, 2017. The sequence of events
 951 has been broken down into key stages of the fire. The defined stages of the fire correspond to periods
 952 where distinctive interactions between the fire, the building, its occupants and the fire brigade were
 953 observed. While different ways of structuring the timeline are possible, in this case, I considered that
 954 for clarity, the stages of the fire timeline were to be separated as follows¹⁸:

- 955 • **Stage One:** From the initiation of the fire event to the breaching of the compartment of origin.
- 956 • **Stage Two:** From the breaching of the compartment of origin to the point when the fire
 957 reaches the top of the building.
- 958 • **Stage Three:** The internal migration of the fire until the full compromise of the interior of the
 959 building, including the stairs.
- 960 • **Stage Four:** Conditions in the building are deemed untenable.

¹⁸ See footnote (1) for approximate times for each stage.

961 3 STAGE ONE: BREACHING OF THE COMPARTMENT

962 3.1 INTRODUCTION

963 All buildings are designed on the understanding that accidental fires will occur. As indicated above,
 964 the fire safety strategy is required to provide adequate management of these events in a manner that
 965 guarantees a performance acceptable to society. In the particular case of a unit in a high-rise building,
 966 the required performance is that the building will prevent propagation of a fire beyond the unit of
 967 origin. Thus, the first aspect to be analysed is how the fire escaped the unit of origin and thus was able
 968 to spread externally both vertically and horizontally. The period between the first report of a fire
 969 (00:54:29) and the first observation of smoke or debris originating from outside the compartment
 970 (01:08:06) is defined as the First Stage of the fire.

971 A number of potential routes for fire spread from the compartment of fire origin to the external
 972 cladding system at Grenfell Tower have been identified in the Phase One expert reports by Dr Lane [4]
 973 and Prof. Bisby [5]. The authors do not identify the exact mechanism by which the
 974 compartmentalization was breached, principally due to the scarcity of reliable data, in terms of both
 975 the exact point of origin of the fire and the contents of the kitchen.

976 With the objective of better identifying the exact mechanism by which the fire breached the
 977 compartment, a simple first principles elimination analysis is conducted here to try to bound the actual
 978 fire scenario within the kitchen more precisely. The nature of the analysis (i.e. simple and adopting
 979 some basic first principles) is necessitated by the constraints imposed by both the complexity of the
 980 problem and lack of reliable data with which to bound the scenario. More complex models can be
 981 used, however these models require greater inputs and a precision that is currently not consistent
 982 with the available information. Major assumptions have had to be made reducing their value to simple
 983 validation of the general physical principles.

984 It is especially important to note that this analysis is conducted from the basis that the origin of the
 985 fire is not established as concluded by Prof. Nic Daeid [2]. If in future more data becomes available,
 986 more complex and exact analytical and computational modelling techniques can be performed to
 987 provide a greater degree of certainty as to the likely mechanism of spread.

988 Prof. Bisby [5] identifies in detail three principle potential routes, corroborated by Dr Lane [4], for the
 989 fire inside the kitchen to ignite the cladding system components:

- 990 Mechanism 1. Fire products (flames and smoke) escaping through the open window and impinging
 991 on the cladding directly ignite the Aluminium Composite Panels (ACPs) above the
 992 window.
- 993 Mechanism 2. Secondary ignition of the kitchen fan leading to direct flame impingement on, and
 994 ignition of, the ACPs above the window.
- 995 Mechanism 3. Loss of structural integrity and / or combustion of the uPVC window surround,
 996 exposing passages by which flames and / or fire products can impinge directly on the
 997 various flammable component materials of the cladding system.

998 This section of the report describes a methodical analysis that aims to bound the fire scenario and in
 999 doing so, address each of these mechanisms within the constraints of the available evidence.

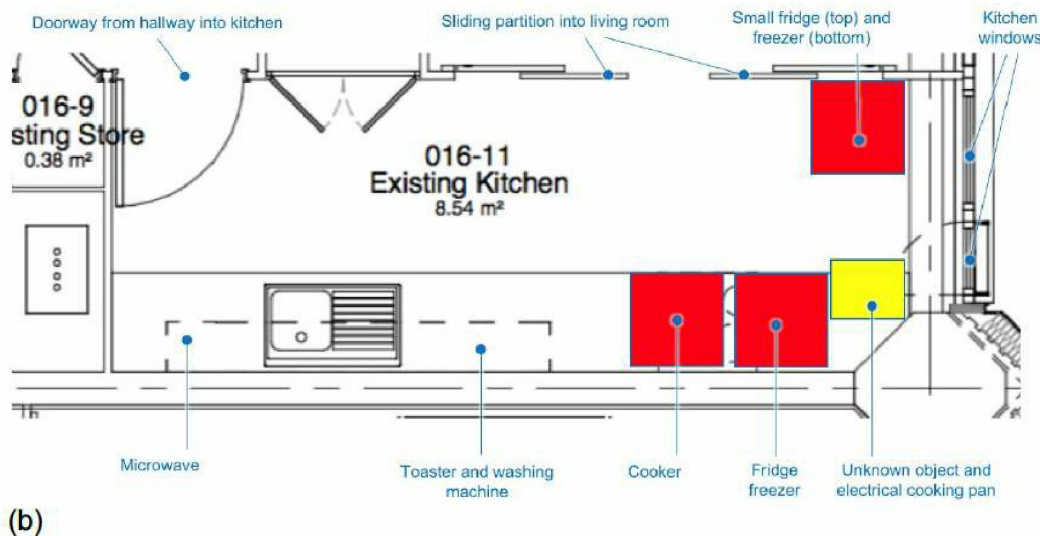


Figure 12 Approximate arrangement of kitchen of Flat 16 a): Photograph 12 from [MET00007748] looking into kitchen from living room; b) annotated extract from design drawing [SEA00000199] showing assumed layout of kitchen at the time of initiation of the fire, which I have prepared based on the available evidence.

FIGURE 2: DIAGRAM TAKEN FROM PROF. BISBY [5] SHOWING THE LAYOUT OF THE KITCHEN OF FLAT 16 AND ITS VARIOUS APPLIANCES (NOT TO SCALE).

3.2 THE FIRE COMPARTMENT

The Bureau Veritas report [3], corroborated by Prof. Nic Daeid [2], identifies that two separate fire events occurred in Flat 16 of Grenfell Tower. The initial event was the fire in the kitchen, which both aforementioned authors agree did not reach flashover. This is corroborated by post-fire photographic evidence of the kitchen [MET00007448] and firefighter statements [MET00005251, MET00005214, MET00005674, MET00005701]. The second event was likely a more significant fire in the bedroom adjacent to the living room, likely a result of re-entry of the fire that had propagated externally via the cladding system.

The compartment comprising the kitchen of Flat 16 is approximately 4.8m long, 1.9m wide, and 2.35m high. The diagram shown in Figure 2 taken from Prof. Bisby [5] shows the layout of the kitchen and the various appliances currently believed to have been present there. The window cavity, located on the east side of the compartment, has a sill height of approx. 1.05m and a total opening height of approx. 1.2m. These dimensions have been extracted from various drawings provided to the inquiry [SEA00000230].

1017 3.2.1 VENTILATION SOURCES

1018 In total, there are three principal ventilation sources in the kitchen; the principal entry door, the
1019 window, and a sliding door connecting to the living room. Thermal imaging camera footage
1020 [MET00005816] suggests that the kitchen door is closed during the kitchen fire phase of the fire, aside
1021 from the time when the flat occupant entered the kitchen to confirm the presence of the fire prior to
1022 evacuating the flat, and during firefighter intervention itself.

1023 The sliding doors to the living room are believed to be closed during the kitchen fire phase, at least up
1024 to the point of firefighter intervention. The flat occupant, who had been sleeping in the adjoining
1025 room, states that he entered the kitchen via the corridor [MET00006339] and Thermal Imaging
1026 Camera (TIC) footage [MET00005816] shows the doors closed at the time of the initial firefighter
1027 intervention.

1028 The flat occupant states [MET00006339] that the window in the kitchen was open by about 10 inches.
1029 Drawings supplied to the inquiry indicate that the windows are tilt and turn windows and that in the
1030 tilt position, the upper side of the windows open approximately 100mm inwards [SEA00000230]. In
1031 the turn position, the windows open fully.

1032 3.2.2 FUEL SOURCES

1033 A number of items known to be present in the kitchen contain flammable materials. These are labelled
1034 in the diagram in Figure 2. Most items are well identified however the exact nature of any objects
1035 between the Hotpoint fridge freezer and the window have not been fully confirmed at the time this
1036 report was written¹⁹. Sufficient detail is not provided in the witness statement by the flat occupant
1037 [MET00006339] or included on the annotated sketch of the kitchen [MET00005190]. It is visible
1038 however in the thermal imaging camera footage [MET00005816] as identified by Prof. Bisby [5]. A
1039 report by Exponent [14] designate this as some kind of cabinet. Prof. Nic Daeid [2] also identifies that
1040 as yet unknown items were likely located there. This is deemed relevant as the occupant that
1041 discovered the fire describes smoke coming from the area between the fridge and the window
1042 [MET00006339] and identifies this area on their sketch, shown in Figure 4. The sketch does not show
1043 anything between the fridge-freezer and the window, however, to the extent of the evidence
1044 available, all other items are apparently shown.

¹⁹ New witness testimony was made available a few days before the submission of this report. This information has not been considered in this report because 1) it does not alter the analysis or conclusions presented here 2) because this information needs to be verified and analyzed by means of appropriate testing. The outcome of this verification analysis and testing might alter some of the details of this report.



FIGURE 3: THE IMAGE FROM [MET00005816] SHOWS AN UNKNOWN OBJECT BETWEEN THE FRIDGE-FREEZER AND THE WINDOW IN FRONT OF THE CORNER COLUMN.

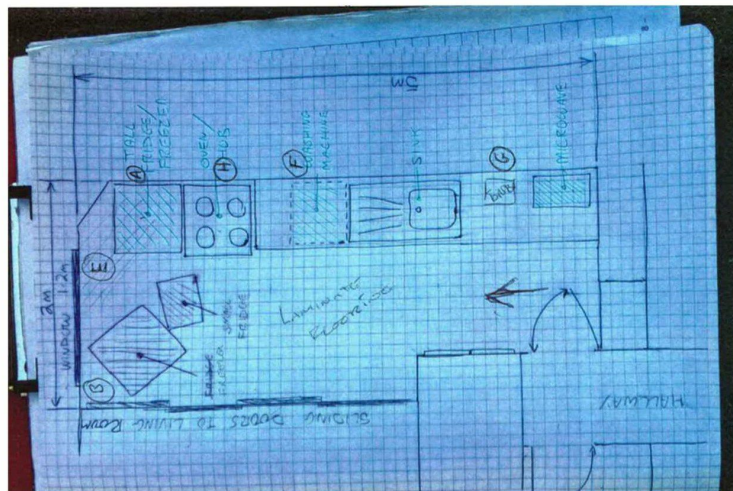


FIGURE 4: SKETCH [MET00005190] PRODUCED ALONGSIDE STATEMENT [MET00006339] OF FLAT OCCUPANT THAT INITIALLY DISCOVERED THE FIRE. LOCATION MARKED E IS THAT IDENTIFIED BY OCCUPANT AS AREA WHERE THEY SAW SMOKE.

1054 3.3 TIMELINE OF THE KITCHEN FIRE

1055 For the purpose of providing a time-scale for the analysis, the following two pieces of evidence bound
1056 the timeline of the kitchen fire:

1057 **00:54:29** - The 999-call reporting the presence of fire is received [MET000080589].

1058 **01:05:57(+2mins)** - The first evidence of fire having reached the cladding system is shown on a video
1059 recovered from a mobile phone [MET000083355]. A still image from this video (shown in Figure 18 in
1060 Section 4) shows molten material / debris falling from the cladding system to the left of the Flat 16
1061 kitchen window as viewed from the outside. Prof. Bisby [5] identifies that the video appears to be two
1062 videos spliced together and thus the timestamp may not be exact. The timestamps on the filenames
1063 of these videos are likely to depend on the accuracy of the clock on the mobile phone device that was
1064 being used. A subsequent video from the same phone [MET000083356] timed at 01:08:06 filmed from
1065 approximately the same location shows the fire at a more advanced stage therefore the clip can be
1066 inferred to have been taken before this, thus between 01:05:57 and approx. 01:08:00.

1067 An image taken by a member of the public at 01:14:53 [MET00006589] shows the fire to be well
1068 established on the outside of the cladding system, again to the left side of the Flat 16 kitchen window
1069 as viewed from the outside. This image is shown in Figure 5.

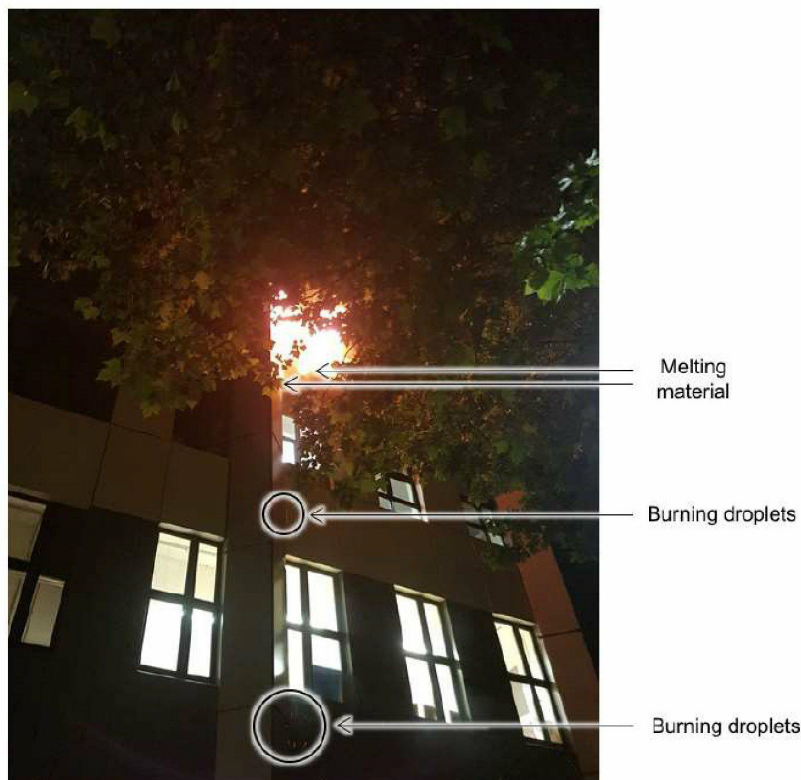


Figure 67 Image [MET00006589] (01:14:53) – annotated.

1070

1071 **FIGURE 5: IMAGE FROM MET00006589 SHOWS A SIGNIFICANT EXTERNAL FIRE ENGULFING THE LEFT SIDE OF THE FLAT**
1072 **16 KITCHEN WINDOW. EXTRACTED FROM PROF. BISBY [5]**

The time of the firefighters' initial interaction with the fire and subsequent entering of the kitchen to extinguish the fire is unclear due to the discrepancy between the time-stamps on thermal imaging cameras used by the first responders. However thermal imaging camera footage of a significant quantity of burning debris / droplets falling past the window moments after the firefighters had initially entered indicates that the fire had already spread to the façade before they entered the kitchen [MET00005816].

The events stated here are also identified in the report by Prof. Nic Daeid [2]. This timeline provides an approximate bounding for any proposed mechanism for fire spread from the kitchen interior to the external façade of approximately 11.5 -13.5 minutes. It is only approximate as it does not include the time taken for activation of the alarm (assumed to be minimal given the size of the kitchen²⁰) and any delay between the occupant discovering the fire and calling 999 (again assumed to be minimal given the occupants' statement [MET00006339]). The reports by Prof. Bisby [5] and Prof. Nic Daeid [4] compile the available information

3.4 BOUNDING THE COMPARTMENT FIRE

Ignition of the flammable components of the cladding system requires the fire within the kitchen to be able to provide a sufficient flux of heat to any component made of combustible materials so as to bring the component to its ignition temperature. This could either be through direct flame impingement, or as a result of sustained contact with smoke and /or heat accumulated in the kitchen at a remote location from the immediate fire plume.

It is also the case with certain polymers that loss of rigidity / stiffness and melting can occur pre- or post-ignition. It is therefore possible that polymer components of the construction can fall or flow away from their original positions when exposed to elevated temperatures, potentially exposing / uncovering other flammable materials.

The following section estimates (1) the fire sizes that might have existed in the kitchen of Flat 16, (2) determines the thermal conditions that could have resulted from them (be that in the direct path of the fire plume or in the hot gas layer that forms), and (3) compares them with the ignition temperatures of the various polymer materials in the cladding system and surrounding the window frame.

3.4.1 MATERIAL PROPERTIES

Table 1 details the relevant material properties of selected polymers applicable to this analysis. These have been taken from the report by Prof. Bisby [5] as well as work from Hidalgo [15] and Ogilvie [16]. It is also of note that uPVC begins to rapidly lose its structural integrity above 60°C, losing 80% of its stiffness by 80°C and 100% of its stiffness by 90°C [17].

²⁰ Smoke detectors will generally activate at the very incipient stages of a fire and therefore the time to detection is normally considered to be very small compared to typical times for fire growth. Given the type of materials present in the kitchen of Flat 16, activation would have been expected to occur when the fire was a few centimetres in diameter. This can be verified through a reconstruction of the event.

1106

| Material | Property | Value |
|---|--------------------------------|-------------------------|
| Polyethylene (PE) | Ignition Temperature (piloted) | 377°C [5], 363-415 [16] |
| Polyisocyanurate (PIR) | Ignition Temperature (piloted) | 306-377°C [5], 377 [15] |
| Unplasticised Polyvinyl Chloride (uPVC) | Ignition Temperature (piloted) | 318-374°C [5] |
| Unplasticised Polyvinyl Chloride (uPVC) | Melting Temperature | 75-105°C [5] |

1107 **TABLE 1: MATERIAL PROPERTIES OF VARIOUS POLYMERS RELEVANT TO THIS SECTION OF THE ANALYSIS.**1108 **3.4.2 FIRE SIZE AND COMPARTMENT TEMPERATURE**

1109 When a combustible material ignites, it starts burning and producing smoke. Smoke migrates towards
 1110 the ceiling accumulating at the top of the compartment. The accumulated smoke is generally referred
 1111 to as a smoke layer (see Figure 6). The height of the smoke layer ("H") will increase in time because
 1112 the fire will continue to produce smoke. The faster the fire grows the faster the smoke layer height
 1113 and its temperature increase. There are several possible scenarios. If there are open vents (e.g. doors,
 1114 windows, etc.) a portion of the smoke will exit the compartment. The loss of smoke decelerates the
 1115 descent of the smoke layer but if smoke cannot flow out faster than it is produced, the smoke layer
 1116 will continue to descend until it fills the compartment. It is likely that the fire will die in this case due
 1117 to lack of oxygen. If the smoke leaving the compartment is the same as the smoke produced by the
 1118 fire then the smoke layer will stabilize. If all the vents are closed the smoke will fill the compartment
 1119 and potentially extinguish the fire due to lack of oxygen. As the smoke layer descends the smoke
 1120 temperature generally increases. The increase in temperature results in heat being transferred from
 1121 the smoke to the unburnt combustibles by radiation. If sufficient heat is transferred, all combustibles
 1122 within the room will ignite. This phenomenon is called "flashover." The relationship between the
 1123 smoke layer height and its temperature is complex and there is no guarantee that the smoke layer will
 1124 reach a temperature that will result in flashover. As indicated above, in the case of Grenfell Tower,
 1125 the fire in the kitchen of Flat 16 did not reach "flashover." The fact that the smoke layer did not reach
 1126 temperatures that resulted in flashover provides evidence that allows for the bounding of the
 1127 temperature of the smoke layer and thus the extraction of important information.

1128 The first step of the analysis estimates the maximum size of fire, known as the Heat Release Rate (HRR)
 1129 (kW), that could exist within the kitchen and that would not bring the compartment to flashover. Next,
 1130 the likely smoke layer temperature range that would result from fires within the kitchen compartment
 1131 is estimated. For this purpose, a simple zone model has been developed which is valid for the time it
 1132 takes to fill the compartment with smoke.

1133 For this model, all openings (doors and windows) are taken as closed. If doors and windows are open
 1134 (it is known, in this case, that the windows were partially open²¹) larger fires could have been attained

²¹ Prof. Bisby [5] indicates (lines 452-457) that smoke was emerging from the window at 1:05:36 but that multiple components of the window were damaged or ignited by then. Figure 58 of the same report shows evidence of smoke at this stage. The amount of smoke is noticeable but not very significant. Given that these first images are approximately 10 minutes into the fire (towards the end of the period being studied), it is very likely that very little smoke would have escaped through the window in the first few minutes of the fire.

before the room filled with smoke. Thus, the present values of the heat release rate should be taken as a lower bound of the heat release rate that will fill the compartment with smoke. The modelling strategy conforms with well accepted practises and provides the information necessary. While very simple in nature, the model precision is consistent with the information available. Details of the model are presented in Appendix A.

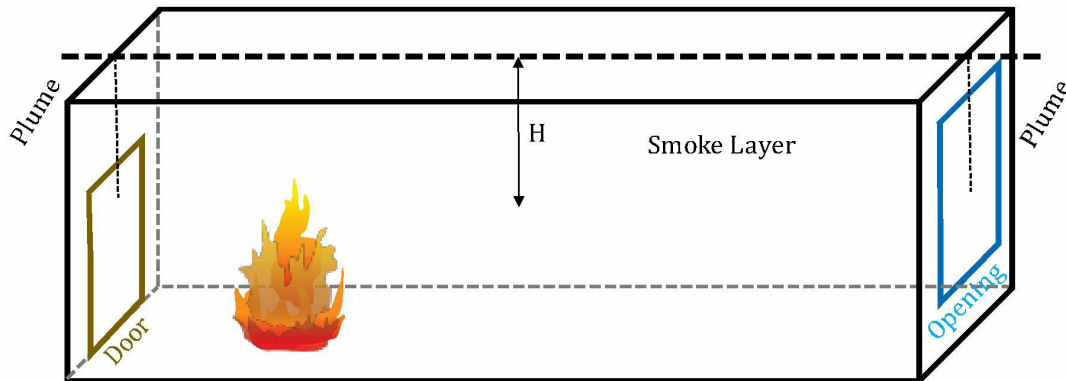


FIGURE 6: SCHEMATIC OF A COMPARTMENT FIRE, “H” IS THE HEIGHT OF THE SMOKE LAYER AND THE WINDOW AND DOOR ARE OPEN.

A simple way of characterizing the growth of the fire is by defining the growth rate of the heat release rate. Simple approaches classify fires as being of slow, medium, fast or ultra-fast growth. The slow and ultra-fast fires will be the extremes. These two extremes have been introduced in the model described in Appendix A and the evolution of the temperature of the smoke layer has been ascertained. The results presented in Figure 7 illustrate the bounding cases, i.e. the slow and ultrafast fires. The curves end when the smoke layer has reached the floor and further temperature increase (or fire growth) is not possible. The smoke layer temperature within the kitchen of Flat 16 would have been somewhere between these two values.

The results show that the compartment fills with smoke very rapidly in both cases, which is to be expected given the small volume of the kitchen.

The model reached a peak HRR before smoke filled the volume of the kitchen during the ultrafast fire growth of the order of 300kW. This corresponds to a hot layer temperature of approximately 220°C. At the lower bound, the slow fire growth results in a peak HRR of approximately 60kW and a hot-layer temperature of approximately 110°C. Limiting the HRR to a peak of 25kW resulted in a temperature slightly above 100°C thus this value is taken as the lower bound. These results are summarised in Table 2.

Given the relatively small fire sizes (i.e. 60-300kW), it is assumed that the available leakage via the open tilted window, and around the kitchen door and partition to the lounge will provide sufficient air supply to maintain the internal fire at these levels but probably no bigger.

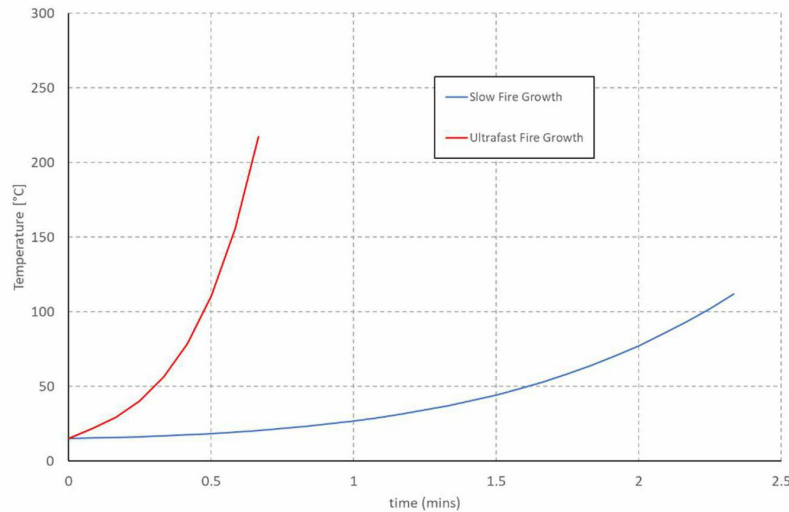


FIGURE 7: THE PLOT SHOWS THE ESTIMATED BOUNDS OF COMPARTMENT TEMPERATURE EVOLUTION DURING THE GROWTH PHASE OF THE KITCHEN FIRE. THE FIRE IN THE KITCHEN OF FLAT 16 WOULD HAVE BEEN SOMEWHERE BETWEEN THESE TWO BOUNDING GROWTH RATES.

| Property | Range |
|--|--|
| Peak Heat Release Rate [Q] | $60\text{kW} < Q < 300\text{ kW}$ |
| Hot-Layer Temperature [T_g] | $100^\circ\text{C} < T_g < 220^\circ\text{C}$ |
| Fire Growth Rate [α] | $0.0029 < \alpha < 0.1876$ |
| Fire Growth Time [t_{growth}] | $40\text{s} < t_{\text{growth}} < 138\text{s}$ |

TABLE 2: BOUNDING CHARACTERISTICS OF THE KITCHEN FIRE GROWTH PHASE. THE PARAMETER “ α ” CHARACTERIZES THE FIRE GROWTH RATE (SEE APPENDIX A)

These values have been subsequently verified with a computation zone modelling tool CFAST²², the output of which correlates well with the values described here. CFAST solves the same equations as those described in Appendix A, but the added functionality of this tool enabled modelling of the scenario with an open kitchen door. The model results show that flashover could be reached if the door was open. If the door is open, then smoke will exit the kitchen allowing for the fire to continue to grow without the smoke layer reaching the floor. This results in higher temperatures and the potential for flashover. The contents of the kitchen were sufficient to deliver a heat release rate greater than 1000 kW which, the model established was the heat release rate necessary to attain flashover. This appears to confirm that the kitchen door was likely closed during this phase of the fire. A description of this modelling and details of the output are described in Appendix B. A simple assessment was made of the impact of having the window partially open. This assessment shows that the area through which the smoke could vent was too small to have an impact on smoke filling. The window was not observed to break during this stage so that scenario was not evaluated.

²² <https://www.nist.gov/el/fire-research-division-73300/product-services/consolidated-fire-and-smoke-transport-model-cfast>

1185 3.4.3 ESTIMATION OF FIRE BASE AREA

1186 An analysis is performed to approximate the area of the base of the fire when the fire sizes identified
1187 above (60 – 300kW) are reached. This analysis is based on the assumed fire growth rates and assumed
1188 characteristic materials. Details of the calculations are presented in Appendix C.

1189 For the slow growth rate fire, the fire area corresponding to the maximum possible heat release rates
1190 equates to a 17 – 20cm radius circular base, or a 29 – 37cm sided square base. By means of
1191 comparison, [12] reports that a 30cm x 30cm pan fire will produce a HRR in the range of approx. 47-
1192 65 kW. This matches well with the 60kW calculated HRR and thus gives confidence in the result despite
1193 the crudity of the technique. For the ultrafast fire growth rate, the fire equates to a 40 – 50cm radius
1194 circular base, or a 68 - 87cm sided square base.

1195 If there was sufficient ventilation to allow for a fire to grow beyond the values reported here (i.e. if
1196 there was extra supply of oxygen that would be available to the fire), the fire would have progressed
1197 to flashover. The photographic evidence shows that the fire did not progress to flashover so it can be
1198 concluded that the kitchen fire would not have been bigger than a 300 kW (40-50 cm radius) fire. The
1199 maximum distance between the fire and any combustible materials that could potentially ignite will
1200 be calculated with this value. This will establish the potential location of the initial fire.

1201 3.4.4 THERMAL PERFORMANCE OF THE UPVC WINDOW SURROUND

1202 The uPVC window surround system is described in detail by Prof. Bisby [5]. This system covers the
1203 existing window frame and extends out to the new windows housed within the cladding system
1204 (Figure 8). As this system extends beyond the original façade to the new windows that are mounted
1205 on a system of Aluminium rails, they also span across the cavity between the window and the original
1206 façade. The uPVC components are adhered to the original window frame with adhesive [5].

1207 Clearly, damage, removal, or poor workmanship could expose the cladding components covered by
1208 this system to a lesser or greater extent, providing a direct path for flames to impinge on the external
1209 flammable materials as highlighted by Prof. Bisby [5] and Dr Lane [4]. Thus, it is important to
1210 understand the effect that elevated temperatures resulting from the fire in the kitchen could have
1211 had on uPVC.

1212 Section 3.3 above lists some relevant properties of uPVC. Of particular interest in this case are the
1213 melting temperature and the elastic modulus shown in Figure 9. The former, with a range of 75 –
1214 105°C, represents the range at which the material will transition from a solid to a liquid. The latter is
1215 closely correlated to the elastic modulus and therefore is a measure of stiffness or the rigidity of the
1216 material and is thus a measure of its ability to support its own weight. The plot in Figure 9 shows that
1217 the material begins to rapidly lose stiffness around 60°C, losing 80% by 80°C and 100% by 90°C.
1218 Logically, this overlaps with the temperature range for melting. It is clear that these temperatures are
1219 well within the range expected in the compartment as per the calculations of Section 3.4.2.

1220

1221

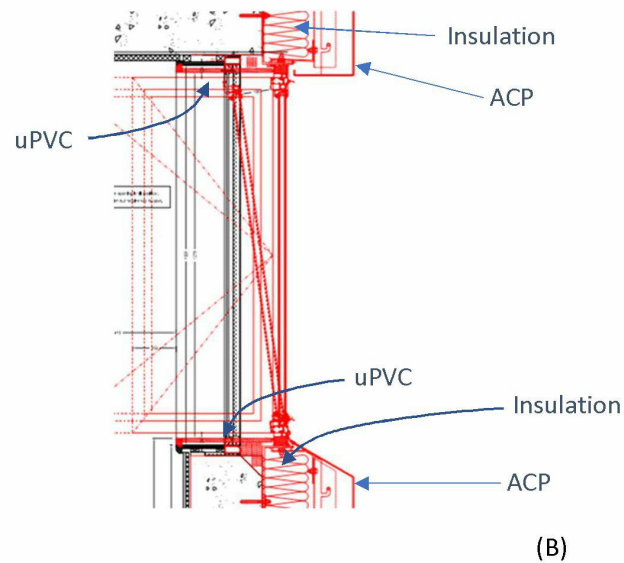


FIGURE 8: THE IMAGE SHOWS A CROSS-SECTION THROUGH THE WINDOW AS DESIGNED [SEA00000230] WITH THE ORIGINAL COMPONENTS SHOWN IN BLACK AND THE NEW SYSTEM IN RED.

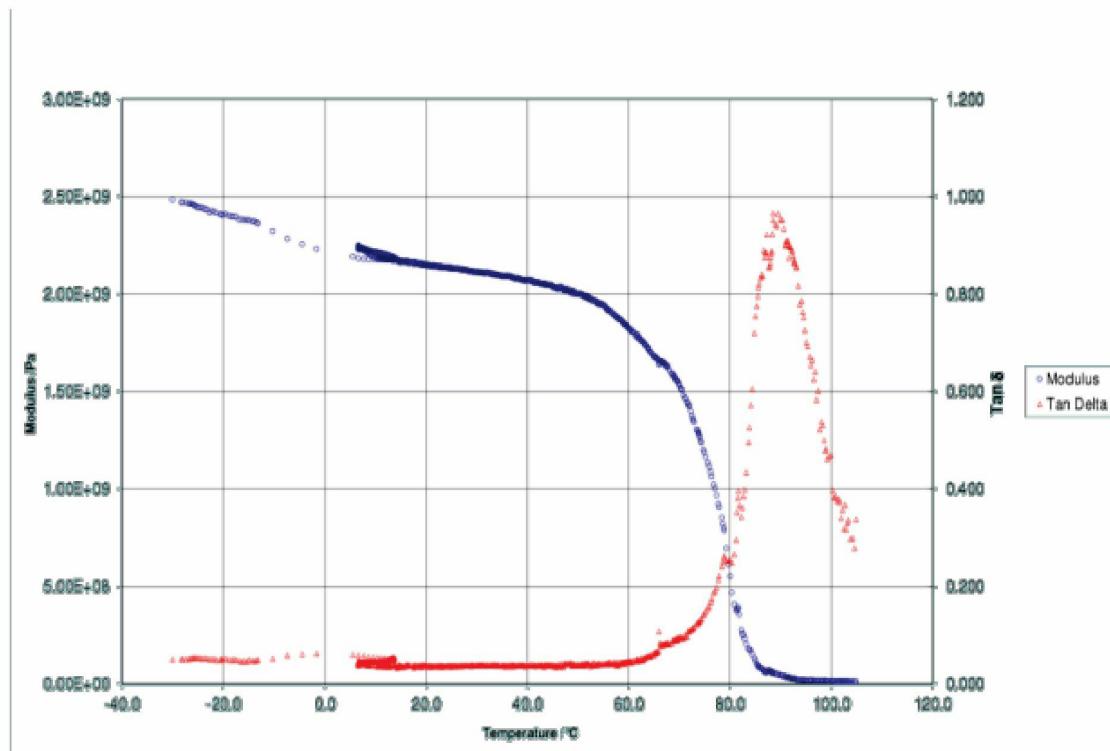


FIGURE 9: MECHANICAL PROPERTIES OF UPVC AS A FUNCTION OF TEMPERATURE [°C]. THE MODULUS (IN BLUE) IS RELATED TO THE ELASTIC MODULUS OF THE MATERIAL. THE PLOT INDICATES THAT THE MATERIAL BEGINS TO DRASTICALLY LOSE STIFFNESS AT APPROX. 60°C, LOSING 80°C BY 80°C AND 100% BY 90°C. TESTS WERE CONDUCTED AT THE UNIVERSITY OF EDINBURGH AND THE DATA WAS PROVIDED BY PROF. BISBY.

1232

1233 Once the material has lost the ability to support itself, it will only be held in place at the locations
 1234 where the bonding adhesive is located (Figure 10). That bonding adhesive is a material which itself will
 1235 be vulnerable to heating and thus is not expected to be functional in this temperature range. Given
 1236 the sparse application of the adhesive, its ability to secure the uPVC at elevated temperatures is
 1237 considered negligible. While demonstrating this sequence of failure is difficult, several examples of
 1238 the uPVC falling due to heating can be observed in post-event inspections (some examples are
 1239 presented in Figure 11) strengthening these arguments.

1240



Figure 55 Line of adhesive used to bond uPVC refurbishment window jamb boards to the pre-existing painted (in this case) timber window jamb board. Considerable use of aluminium tape within refurbishment window frame construction [My photo, Flat 13, 09/01/2018].

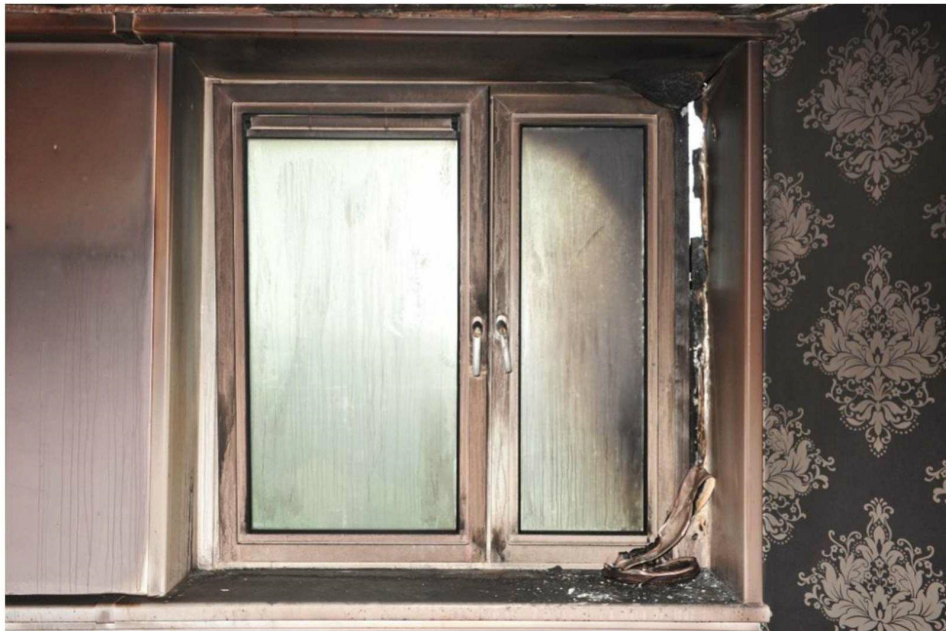
1241

1242 **FIGURE 10: IMAGE OF THE ADHESIVE TAKEN FROM PROF. BISBY [5].**

1243

1244 Photographic evidence obtained following the fire at the Grenfell Tower has identified many instances
 1245 of this type of failure as shown in Figure 11. It should be noted that these elements do not all show
 1246 signs of charring implying that they did not all combust but simply lost stiffness. Typically, it is the head
 1247 and jambs that exhibit de-bonding as this mechanism is gravity assisted for these elements.

1248



1249

1250

(A)

1251



1252

1253

(B)



(C)

FIGURE 11: A RANGE OF EXAMPLES OF DEBONDING OF UPVC ELEMENTS OF THE WINDOW SURROUNDS DUE TO HEAT EXPOSURE. (A) SHOWS DEBONDING OF A WINDOW JAMB THAT HIS LOST RIGIDITY DUE TO HEATING FROM THE EXTERNAL FIRE CREATING AN OPEN PASSAGE BETWEEN THE INTERIOR AND EXTERIOR. (B) SHOWS THE WINDOW UPPER PEELING AWAY (C) SHOWS THE MAIN WINDOW JAMBS DEBONDING FROM THE SIDE OF THE WINDOW CAVITY.

A simple energy storage analysis is conducted to approximate the change in temperature of the uPVC as a result of exposure to the hot-layer gases (details of the analysis are presented in Appendix D), and thus establish if any thermal degradation of the material is possible within the timeframe provided by the evidence in Section 0. The results of the model are presented in Figure 12. They illustrate the range of effects that a fire, within the ranges defined by the limited evidence, could have on the uPVC.

The lower bound, defined by a slow growing fire reaching a peak HRR of 60kW and a hot-layer temperature of 100°C, brings the uPVC to a temperature of approx. 65°C within the 11.5 minute timeframe. This, as stated earlier, is slightly above the onset temperature of rapid loss of stiffness (60°C).

The upper bound, defined by an ultrafast growing fire peaking at a HRR of 300kW and a hot-layer temperature of 220°C, brings the uPVC to 150°C within the 11.5 minute timeframe, reaching the point of loss of 100% stiffness (90°C) in less than 5.5 minutes.

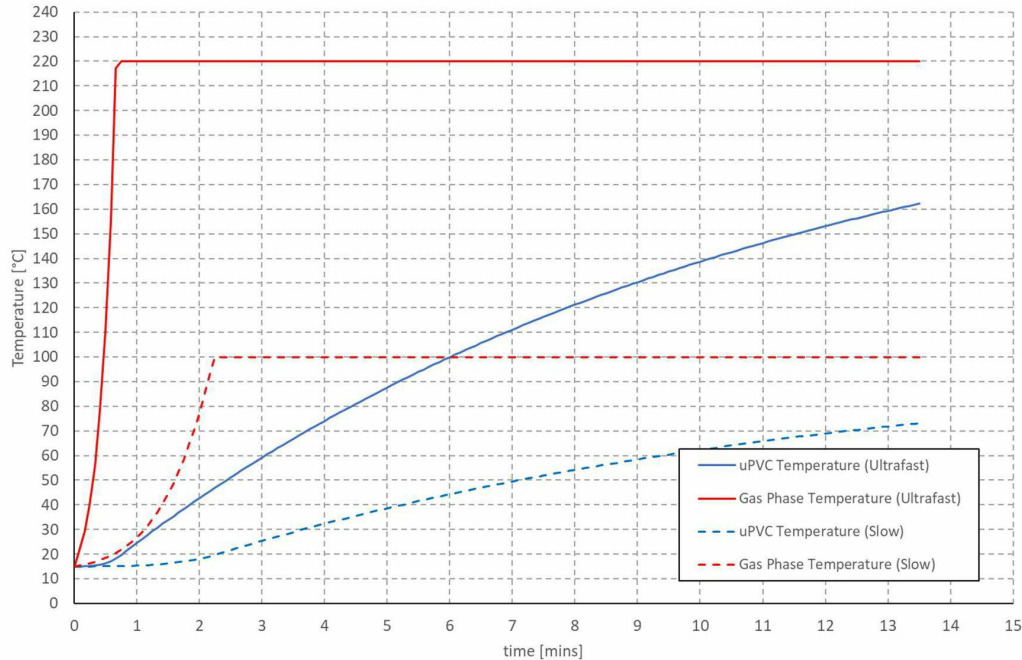


FIGURE 12: THE PLOT SHOW THE BOUNDING GAS PHASE TEMPERATURES (RED) AND RESULTANT SOLID PHASE (UPVC) TEMPERATURES (BLUE). THE LOWER LIMIT IS DEPICTED BY DASHED LINES, AND THE UPPER LIMIT BY SOLID LINES.

The minimum conditions required to bring the 9.5mm thick uPVC to a temperature of 90°C within the 11.5 minute timeframe are a fire growth rate, α , of 0.0091kW/m² which falls between the slow (0.0029) and medium (0.0117) fire growth rates, reaching a peak HRR of 90kW and peaking at a temperature of 140°C.

From these results, it can be concluded that most fires originating from fuels typical of a domestic kitchen will have the capacity to significantly damage the uPVC. It is very likely that the loss of stiffness will result in deformations and the generation of gaps. The adhesive, as it was applied, will have no capacity to prevent this.

3.5 MECHANISMS OF IGNITION OF AN EXTERNAL FLAME

The maximum temperature of the smoke layer cannot exceed 220°C even if an ultra-fast fire is considered (Figure 12). Ignition of the combustible materials of the façade surrounding the window requires at least 306°C (Table 1). Therefore, ignition of any of the combustible facade materials by means of the smoke layer is not possible. Ignition must occur by means of direct impingement of the flame.

Different hypotheses regarding the cause and origin of the fire have been postulated and described in detail in the Phase 1 Expert Report submitted by Prof. Nic Daeid [2]. Prof. Bisby's Phase 1 Expert Report also provides information on the different means by which the fire started [5]. This report will not expand on matters of cause and origin.

From the analysis presented so far in Sections 3.3 and 3.4 it is clear that the most significant events leading to the involvement of the façade elements in the fire would have occurred within the first 5 minutes from ignition. The reports by Prof. Nic Daeid [2] and Prof. Bisby [5] establish that with the exception of the occupant witness statement [MET00006639] there is no other information on that period. A detailed analysis of the fire scene after the event would have also been able to provide some additional information, nevertheless, this information is not presented in the available forensic reports [3]. Despite the limited information, Prof. Bisby postulates three hypotheses in his Phase 1 Expert Report [5]. These are transcribed here for clarity:

Line 575. "Hypothesis B1: The route of fire spread from inside the kitchen of Flat 16 to the external cladding was via the infill sandwich panel within which the extract fan was mounted, or via the extract fan itself, and igniting the external cladding adjacent to the kitchen window of Flat 16. This subsequently led to sustained burning of the external cladding."

Line 579. "Hypothesis B2: The route of fire spread from inside the kitchen of Flat 16 to the external cladding was due to flame impingement from the internal fire venting from the window opening. This subsequently led to sustained burning of the external cladding."

Line 582. "Hypothesis B3: The route of fire spread from inside the kitchen of Flat 16 to the external cladding was due to parts of the internal window surround and external cladding system being penetrated by the fire, thus allowing fire spread directly into the back of the cladding cavity from within the room of origin. This subsequently led to sustained burning of the cladding either within the cavity or on its external surface, or both."

Hypothesis B1, as indicated by Prof. Bisby [5], is highly unlikely and very easily disproven by means of testing. Section 6.10.2.4 in Prof. Nic Daeid's Expert Report [2] indicates that "the extractor fan associated with the kitchen window of Flat 16 can be eliminated as being within the area of origin of the fire as no physical evidence of electrical damage has been observed." The materials present in the fan and casing (type and quantity) are too small to provide a sufficient heat flux to ignite the cladding by means of external flames [16]. A simple analysis that demonstrates this will be provided in Section 3.5.3. This analysis uses a simplified geometry and cannot be conclusive because geometrical intricacies of the assembly might affect the flame geometry and subsequently the heat flux distribution. While very unlikely, the hypothesis cannot be completely discarded with the current information, nevertheless, a test can serve to exclude this hypothesis. This should be a matter for Phase 2.

Hypothesis B2 can be split into two different cases, the first case corresponds to the gases from the smoke layer venting from the window and subsequently igniting the cladding, the second is flames close enough to the window so that they can directly vent from the window opening. The first case can be discarded on the basis that the smoke layer would have never been hot enough for the smoke venting from the window to ignite the cladding. The second scenario is a subset of Hypothesis B3 given that the window surround will be much closer to the fire than the cladding, thus would have most likely ignited first by direct impingement of flames. The following analysis will address the scenario of direct impingement. This is consistent with the conclusion of Prof. Bisby [5] who states:

Line 597. "There is insufficient evidence to fully accept Hypothesis B3 at present. However, on the balance of probabilities and the evidence presented in this section, I consider Hypothesis B3 to be the most likely, by a considerable margin, of hypotheses B1, B2, and B3."

As stated by Prof. Bisby [5], the following sequence of events is necessary before the fire could spread into the cladding cavity.

Line 585. “(1) The uPVC window boards forming the sill, jamb, or head of the internal window framing enclosure would have to be penetrated or removed;”

Line 586. “(2) The thermal insulation applied to the back face of the uPVC window boards would have to be penetrated or removed; and”

Line 587. “(3) The EPDM rubber membrane would have to be penetrated (or not be present in that location).”

Details of all these components are presented in Sections 4.5 to 4.9 of Prof. Bisby’s Phase 1 Expert Report. Section 3.4.4 of this present report has shown that it is very likely that in the presence of the smoke layer the uPVC would have deformed establishing paths for the fire to reach any of the other components (EPDM Synthetic Rubber Membrane, PIR insulation and ACP panel). None of these components would have ignited with the temperatures attained by the smoke layer, therefore the conditions that will lead to direct impingement of flames on these materials need to be analyzed.

A series of potential scenarios for the origin of the fire were established by the Phase 1 Expert reports of Prof. Nic Daeid (Section 6.10.2) [2] and Prof. Bisby (Section 5.7.2) [5]. These scenarios require the analysis of two conditions, an open fire that could directly impinge on the materials part of the window assembly or a fire occurring behind an appliance/obstacle, where the flame will have to migrate to the ceiling before travelling towards the window assembly. Figure 13 shows a schematic of the two conditions.

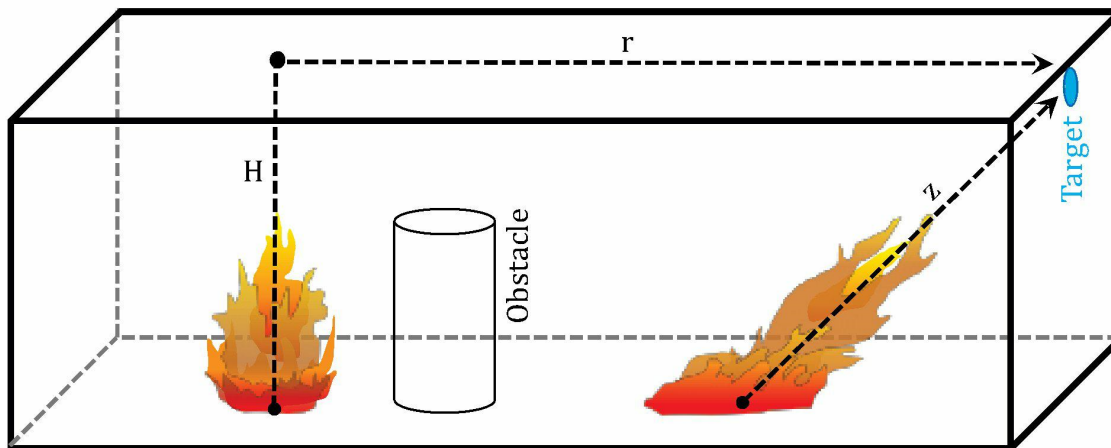


FIGURE 13: SCHEMATIC OF THE TWO CONDITIONS TO BE ANALYZED, DIRECT IMPINGEMENT OVER A DISTANCE “ z ” OR FIRE BEHIND AN APPLIANCE/OBSTACLE WHERE THE FLAMES HAVE TO FIRST REACH THE CEILING AND THEN PROGRESS TOWARDS THE TARGET FOLLOWING A PATH “ $H + r$.”

The following sections will use very simple analysis methods. These methods are not necessarily very precise or strictly valid for the conditions of the Grenfell Tower fire, nevertheless the results serve to provide a clear idea of scenarios that can be discarded. If more precise methodologies become necessary, these will be used as part of subsequent reports.

3.5.1 IGNITION BY DIRECT IMPINGEMENT

This part of the analysis aims to determine what are the necessary conditions where direct flame impingement could result in ignition. This is depicted by the diagram in Figure 14. A plot created by McCaffrey [18], reproduced in Figure 15, is used to establish the characteristics of the fire in the kitchen that could lead to ignition of various flammable components. The ignition temperatures of each component material are used to define the value of $\Delta T = T_{ig} - T_a$ (T_{ig} is the ignition temperature and T_a the ambient temperature). “z” is defined as the height above the base of the fire (m) at which the flame or plume comes into direct contact with the flammable material. Using these two values and the plot in Figure 15, \dot{Q}_c , the convective portion of the heat release rate, can be established. The total HRR, \dot{Q} , is then established from the following relationship [20]

$$\dot{Q}_c = \frac{\dot{Q}}{1.5}$$

EQUATION 1

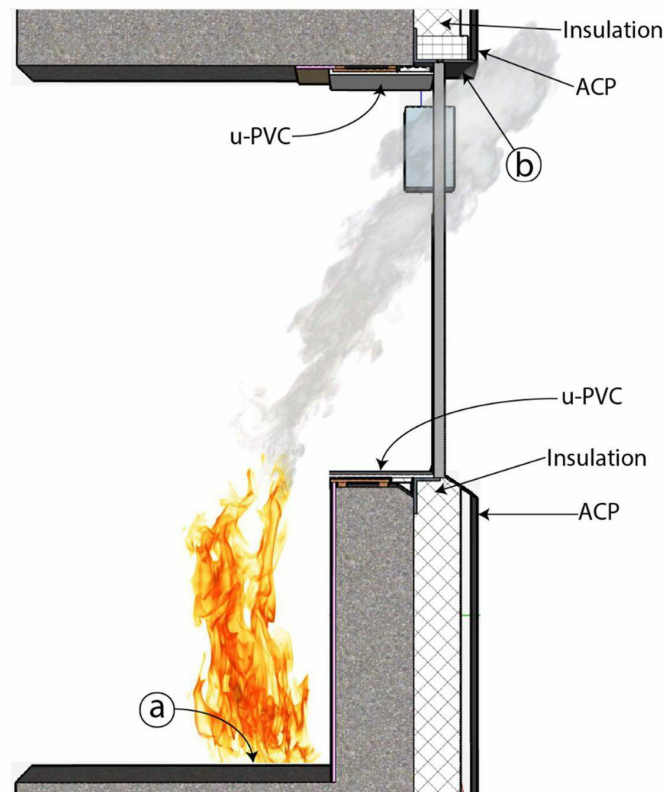


FIGURE 14: THE DIAGRAM ILLUSTRATES THE WINDOW AND CLADDING SYSTEM AS CONSTRUCTED AT THE TIME OF THE FIRE. IT ILLUSTRATES THE CONCEPT OF FLAME AND PLUME IMPINGEMENT ON THE FLAMMABLE MATERIALS AROUND THE WINDOW CAVITY.

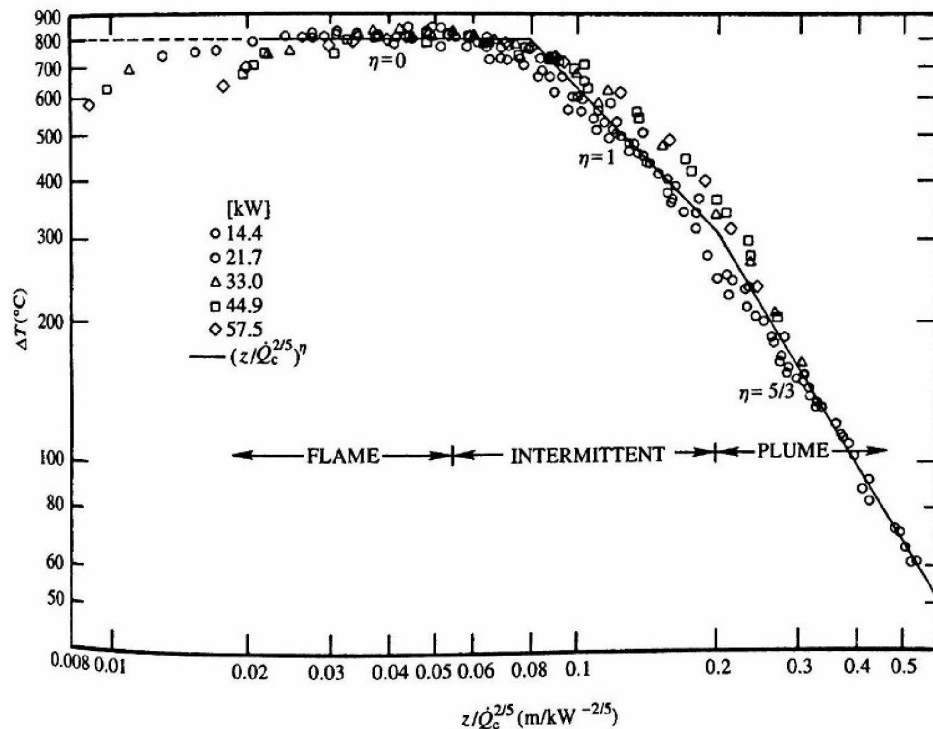


FIGURE 15: PLOT BY McCaffrey [18] REPRODUCED FROM Drysdale [21] CORRELATING THE INCREASE IN TEMPERATURE ABOVE AMBIENT WITHIN THE FIRE PLUME WITH THE HEAT RELEASE RATE AND HEIGHT ABOVE THE BASE OF THE FIRE.

Using the example of Hypothesis B3 depicted in Figure 14, the ignition temperature of the Polyethylene in the ACP panel is given in Table 1 as 377°C , thus $\Delta T = T_{\text{ig}} - T_a = 362^{\circ}\text{C}$. Using the plot in Figure 15, this equates to a value of $\left(\frac{z}{\dot{Q}_c^{2/5}}\right)^{\eta} = 0.18$ where $\eta = 1$ and is located in the intermittent plume.

The distance “z” is approx. 2.3m (point a to point b in Figure 14), thus solving for \dot{Q}_c , and subsequently for \dot{Q} , gives a required HRR of 875kW to ignite the ACP panel above the window (point b) from direct flame / plume impingement from a fire within the kitchen at floor level, immediately beneath the window (point a). This method is reproduced for the three relevant ignitable materials, for the range of relevant heights i.e. top to bottom of the window cavity. Table 3 summarises the results from this analysis.

There are two columns of results presented in Table 3. The ‘Smallest Fire’ column represents the smallest fire located, at floor level, necessary to cause an ignition of the given material at the given location. For example, the uPVC window surround can theoretically be ignited at the sill level by a 20kW fire, however would need a 120 kW fire to ignite it level with the top of the window. Heights in between would require a fire size, at this location, between these two bounding values. The PIR insulation shows similar requirements in terms of fire size. For means of illustration, Figure 16 shows two buoyant flames, the smaller ≈ 25 kW and the large ≈ 75 kW.

The second group of results labelled 'max distance', represents the maximum horizontal distance that the largest possible fire (300 kW) could be from the base of the wall beneath the window, in order to result in an ignition via direct impingement. This assumes a tilted plume forming a straight line between the base of the fire and the ignition location.

| Material | Window Location | Smallest Fire [kW] | Max Distance [m] |
|--------------------|-----------------|--------------------|------------------|
| uPVC | Top | 120 | 2.4 |
| | Bottom | 20 | 3.1 |
| Polyethylene (ACP) | Top | 830 | No Ignition |
| | Bottom | 125 | 1.2 |
| Insulation (PIR) | Top | 110 | 2.5 |
| | Bottom | 20 | 3.2 |

TABLE 3: RESULTS FROM THE McCaffrey Plot. SHOWS BOTH THE SMALLEST FIRE THAT COULD IGNITE THE MATERIAL AT A SPECIFIED LOCATION AND THE FURTHEST A FIRE COULD BE TO IGNITE A MATERIAL WITHOUT REACHING FLASHOVER

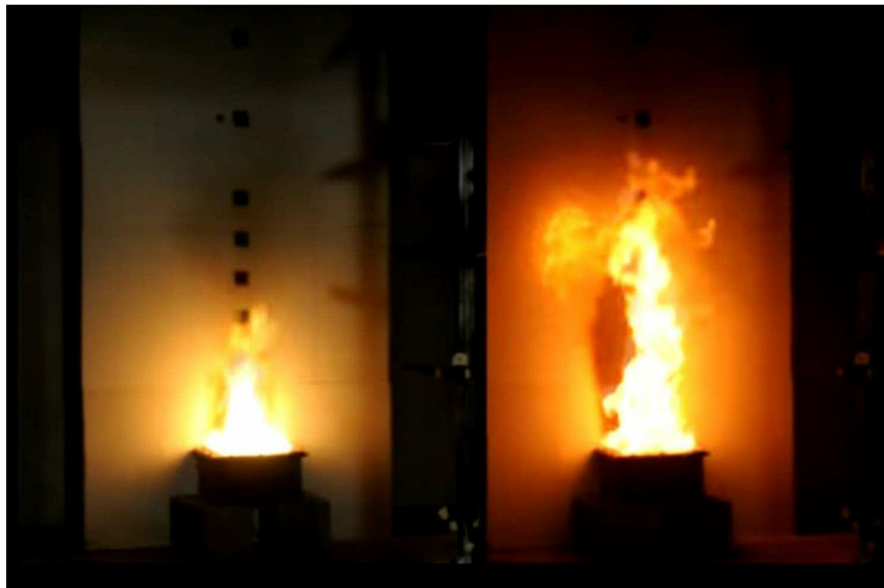


FIGURE 16: TWO BUOYANT FLAMES, THE LEFT APPROX. 25 kW AND THE RIGHT APPROX. 75 kW, FROM [HTTPS://WWW.YOUTUBE.COM/WATCH?V=7B9-bZCCUxU](https://www.youtube.com/watch?v=7B9-bZCCUxU).

Table 3 indicates that a fire located at ground level of 300 kW of less, could not provide the required ΔT to cause ignition of the ACP directly above the window. The base of a 300kW fire would have to be within 1.5 m (direct line) of the ACP outside the window to be capable of causing direct ignition via flame / plume impingement. A fire at floor level, even directly beneath the window, would need to be

1421 of the order of 830kW to ignite the ACP through the window. A fire of this size, with the compartment
 1422 ventilation as it was, would have brought the compartment to flashover, thus is not consistent with
 1423 the evidence.

1424 3.5.2 FIRES BEHIND AN OBSTACLE

1425 If the plume originating from a fire at floor level is obstructed by appliances and unable to directly
 1426 impinge on the flammable materials around the window (Figure 13), impingement must occur
 1427 indirectly. The flames must migrate first towards the ceiling and then travel horizontally as a ceiling
 1428 jet until reaching a combustible component. This scenario corresponds to the fire suggested as having
 1429 its origin in the Hotpoint FF1758P.

1430 A correlation by Alpert [22] that describes the decay in temperature of the smoke products as they
 1431 travel horizontally across the ceiling is used to determine the Heat Release Rate (HRR) required from
 1432 an obscured fire to ignite PIR and uPVC materials at ceiling height, as a function of distance from the
 1433 window of a ground level fire. The temperature of the ceiling jet, T_{max} [°C], in the area where the plume
 1434 impinges on the ceiling is given by Alpert as:

$$1435 \quad T_{max} = T_{\infty} + \frac{16.9\dot{Q}_c^{\frac{2}{3}}}{H^{\frac{5}{3}}}$$

1436 EQUATION 2

1437 Where T_{∞} [°C] is the ambient temperature, \dot{Q}_c [kW] is the convective portion of the heat release rate,
 1438 and H [m] is the height of the room. The radius of impingement r [m] is defined as $0.18H$. Outside of
 1439 this radius, the temperature of the ceiling jet is defined as:

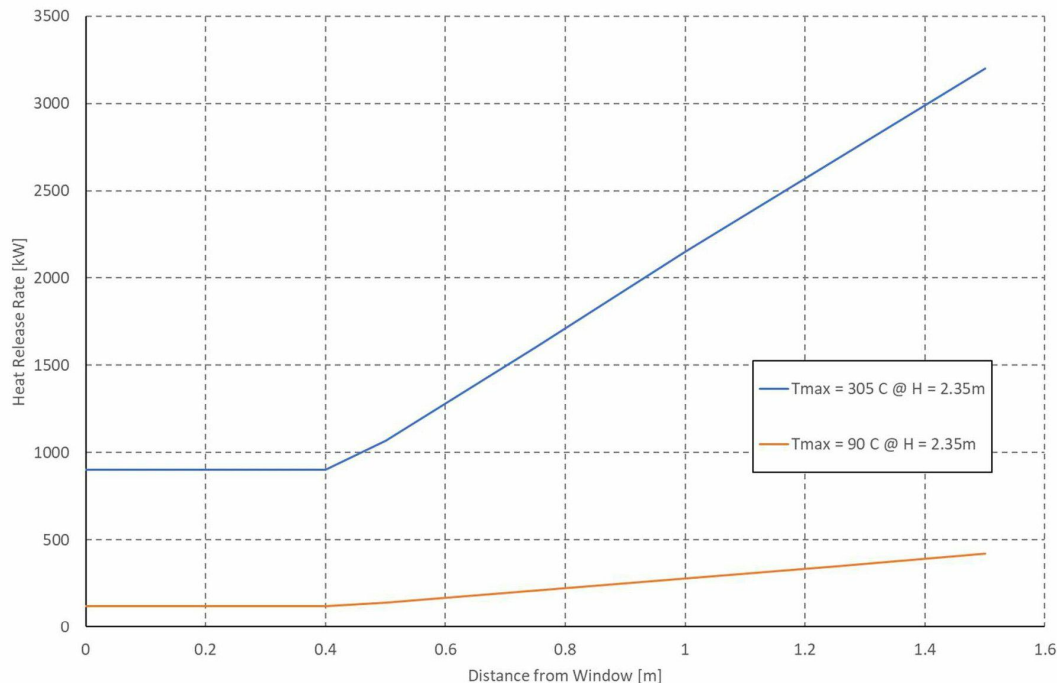
$$1440 \quad T_{max} = T_{\infty} + \frac{5.38\left(\dot{Q}_c/r\right)^{\frac{2}{3}}}{H}$$

1441 EQUATION 3

1442 The lower bound of the range of ignition temperatures of PIR (insulation) and uPVC (window surround)
 1443 is approx. 305°C. The blue line in Figure 17 shows the HRR required to produce a ceiling jet
 1444 temperature above 305°C at the top of the window if the fire is at floor level. The horizontal axis shows
 1445 the distance between the fire and the external wall. In all cases, the required HRR is of sufficient
 1446 magnitude that the fire would be expected to result in flashover. This implies that only direct,
 1447 unimpeded flame / plume impingement would result in ignition of these materials at the upper
 1448 window level.

1449 A fire that starts at the floor level and finds combustible materials to spread vertically can eventually
 1450 produce temperatures that could ignite ceiling covers (i.e. PURLBoard (Section 4.2.3 [5]: Line 312: “a
 1451 band approximately 350 mm wide on the ceiling around the entire exterior perimeter of all intact and
 1452 partially intact flats”)) or potentially find its way to the window. Proof of the viability of any scenario
 1453 of this nature will require the testing of the fire source with the potential source of ignition. These
 1454 tests should be carefully instrumented to quantify all relevant variables and should be undertaken as
 1455 part of a Phase 2 analysis.

1456 The orange line in Figure 17 indicates the HRR required to attain a temperature of 90°C impinging on
 1457 the window. This corresponds to the temperature at which the uPVC will lose its structural integrity.
 1458 The plot indicates that the initial ceiling jet of a fire less than 300kW in size, at floor level up to 1m
 1459 away from the window, could result in smoke impingement on the uPVC at 90°C.



1460

1461 **FIGURE 17: THE PLOT SHOWS: BLUE LINE - THE HRR [kW] REQUIRED TO PRODUCE A CEILING JET WITH SUFFICIENT**
 1462 **TEMPERATURE TO IGNITE PIR AND uPVC COMPONENTS AT THE TOP OF THE WINDOW, AS A FUNCTION OF THE DISTANCE**
 1463 **[M] OF THE ORIGINATING FIRE FROM THE WINDOW AT FLOOR LEVEL. ORANGE LINE - THE HRR [kW] REQUIRED TO**
 1464 **PRODUCE A CEILING JET WITH SUFFICIENT TEMPERATURE TO CAUSE THE uPVC TO LOSE 100% OF ITS STRUCTURAL**
 1465 **INTEGRITY [90°C].**

1466 3.5.3 THE FAN AND FAN MOUNTING UNIT AS AN IGNITION SOURCE OF THE ACP

1467 In the same video that indicates the first instance of spread to the cladding [MET000083355], flames
 1468 are visible in or around the location of the fan and its mounting panel. This is shown in detail by Prof.
 1469 Bisby [5] and leads to Hypothesis B1. It is not clear from the video footage if it is the fan and / or the
 1470 fan mounting panel that are alight, or if it is a flame emerging from the window beneath the mounting
 1471 panel. Prof. Bisby indicates that the source of the flame is initially located at the base of the mounting
 1472 panel, thus for this to be the ignition source of the ACP panels, the flame either had to originate in the
 1473 compartment or, by some means of exposure due to failure of the window system, originate from the
 1474 base of the fan mounting panel. The former has been addressed in Section 3.5 The latter is addressed
 1475 here. The report by Dr Lane [4] gives dimensions of the fan mounting panel as approx. 0.5 x 0.5 m,
 1476 with a 1.5 mm aluminium skin either side of a 25mm thick PIR core.

1477 Assuming the underside of the fan mounting is burning, the methodology described in Appendix C is
 1478 used to establish an upper bound heat release rate of approximately 5 kW. Using the plot by McCaffrey

1479 in Figure 15, the flame and plume resulting from this fire would have a temperature above the ignition
 1480 temperature of any of the combustible materials for less than 30cm from its base. This means that the
 1481 temperature in the plume issued from a fire at the base of the mounting panel could have not ignited
 1482 the ACP panel or any of the combustible materials present in the façade system.

1483 3.6 RELEVANT ACTIVE AND PASSIVE FIRE SAFETY SYSTEMS

1484 As indicated in Table A [4], the following items would have been relevant to preventing a typical
 1485 residential kitchen fire from impacting the building beyond Flat 16:

- 1486 • The loadbearing elements of structure of the building are capable of withstanding the effects
 1487 of fire for an appropriate period without loss of stability; Structural Stability - Temperatures
 1488 between 100 - 220°C will pose no challenge to any of the structural systems. Therefore, the
 1489 structure can be deemed to be sound.
- 1490 • The building is sub-divided by elements of fire resisting construction into compartments;
 1491 Compartmentalization – Only the south facing wall of the kitchen serves as boundary to a
 1492 different unit, thus is required to provide compartmentalization. Temperatures between 100
 1493 - 220°C will pose no challenge to this wall. The walls facing outwards are not required to
 1494 maintain compartmentalization (Line 3.4.2 [4]), thus window system and glazing are not
 1495 included in this requirement. Therefore, compartmentalization is maintained.
- 1496 • Any openings in fire separating elements are suitably protected in order to maintain the
 1497 integrity of the element (i.e. continuity of fire separation); Fire stopping – This requirement
 1498 only pertains to the south facing wall of the kitchen and there is no evidence that there was
 1499 any fire stopping on this wall.
- 1500 • Any hidden voids in the construction are sealed and sub-divided to inhibit the unseen spread
 1501 of fire and products of combustion, in order to reduce the risk of structural failure and the
 1502 spread of fire, insofar as they pose a threat to the safety of people in and around the building;
 1503 Cavity barriers – Given that the uPVC window surround acted as a barrier between the façade
 1504 system cavities and the compartment, these should have inhibited the spread of fire and
 1505 products of combustion. Given the low temperatures that will breach this barrier (less than
 1506 90°C), any fire common to a residential kitchen would have resulted in failure of the intended
 1507 barrier in a few minutes (less than 12 min for Grenfell Tower).

1508 3.7 SUMMARY

- 1509 • The photographic evidence indicates that this fire never reached flashover [2,3].
- 1510 • Analysis based on the geometry of the compartment and the known ventilation conditions (door
 1511 and window closed) establishes that a fire would have reached a steady temperature between
 1512 100°C-220°C. These temperatures are below those capable of inducing flashover. These
 1513 temperatures are not capable of igniting any of the combustible components adjacent to the
 1514 window.
- 1515 • If the door and main window were to provide a means for smoke to exit the kitchen, a fire in
 1516 excess of 300 kW would have brought the room to flashover. This indicates that it is most likely

- 1517 that the door to the kitchen (as well as the partition) must have been closed for most of the initial
 1518 stages of the fire.
- 1519 • The fire that occurred in the kitchen of Flat 16 of the Grenfell Tower would have not exceeded
 1520 300 kW and a lower bound approximation for the temperatures of the smoke would have been
 1521 between 100°C-220°C.
 - 1522 • Heating of the uPVC by smoke between 140°C - 220°C would have resulted in the uPVC reaching
 1523 temperatures that led to total loss of its mechanical strength in a period between approx. 5 - 11.5
 1524 min.
 - 1525 • A fire of characteristics common to any residential kitchen fire would have therefore resulted in
 1526 the loss of strength of the uPVC surrounding the window. This would have happened within a
 1527 period consistent with the time gap between the first observation of the fire and the first evidence
 1528 of involving external to the building (11.5 - 13.5 min) [2].
 - 1529 • The dimensions of the kitchen are sufficiently small that the location of the fire is irrelevant when
 1530 it comes to breaching the uPVC by loss of mechanical strength. This failure can be deemed as a
 1531 failure of the barrier to protect the cavity.
 - 1532 • The uPVC served as the single barrier between the interior of the building and the components of
 1533 the cladding system. Thus, after breaching the uPVC barrier, any of those components would have
 1534 been exposed.
 - 1535 • Given the low temperatures of the smoke, ignition of the combustible components adjacent to
 1536 the window requires direct flame impingement.
 - 1537 • Given that flashover was not observed, the maximum fire size that will not result in flashover was
 1538 used to determine how far from the window this fire could be. A fire of 300 kW will have to be at
 1539 the most 3m way from the window to ignite any of the combustible materials adjacent to the
 1540 window.
 - 1541 • Therefore, as an upper bound, a fire of characteristics common to a kitchen fire and that will not
 1542 lead to flashover (less than 300 kW), if placed within 3 m of the window, is capable of triggering
 1543 external flame spread.
 - 1544 • As a lower bound, a fire at floor level directly beneath the window, greater than 20kW, is capable
 1545 of igniting exposed flammable materials (PIR, uPVC) at window sill level via flame/plume
 1546 impingement, thus potentially leading to ignition of external cladding and external fire
 1547 propagation.
 - 1548 • Flames from fires behind an obstacle will have much longer paths, therefore will require larger
 1549 fires in order to cause direct ignition of combustible materials within the cladding system. Given
 1550 the narrow window, it is probable that any obstructed fire capable of igniting any of the window
 1551 materials will have to be of such a magnitude that it would have led to flashover.
 - 1552 • An obstructed fire that finds combustible materials to spread upwards cannot be discarded as a
 1553 potential source of ignition of the combustible materials that make up the cladding system.
 - 1554 • The extent of burning as a result of secondary ignition of the fan / fan mounting unit is not
 1555 sufficient to induce ignition of the ACP panels as a result of plume impingement.
 - 1556 • Evidence of initial dripping and external flame development point to ignition of the cladding to
 1557 the left side of the kitchen window as viewed from the outside.
 - 1558 • Temperatures between 100°C - 220°C will pose no challenge to any components of the structure.
 1559 Therefore, the structure can be deemed to be sound. Furthermore, a fire of this nature would
 1560 have not been perceived by occupants or firefighters as a challenge to structural stability.

- 1561 Structural stability is essential to enable egress and firefighting operations. The perception that
1562 the structure might be compromised could also affect decision making.
- 1563 • The size of the fire that breaches the uPVC and the size of the fire that will ignite the exposed
1564 combustible materials of the façade system are within a range that can be considered as a feasible
1565 event within a residential kitchen. Many activities and appliances could serve as sources of ignition
1566 and can experience a fire consistent with the values reported here (less than 300 kW). The
1567 probability of such an event can therefore be considered one.
 - 1568 • Given that the initial fire event cannot be considered unusual in any way, determination of the
1569 cause and origin of the fire is therefore of secondary relevance to the definition of the
1570 development of the fire after ignition of the façade system.

4 STAGE TWO: VERTICAL FIRE SPREAD

4.1 VERTICAL FIRE SPREAD AT GRENfell TOWER

Once the fire enters the façade system it initiates its spread outwards and then upwards. The first image where flaming debris and smoke is observed emerging outside the compartment is presented in [2] and timed stamped at 01:05:57 (see Figure 18 from [2]). By 01:14 the fire is visibly established on the outside the building (Figure 19) and has compromised many components of the façade system and by 01:26 it has propagated upwards past floor 18 (see Figure 20 from [4]). The fire appears to reach the architectural crown of the building before 01:30. During the process of vertical flame spread the fire does not propagate in the south direction (contained by the column) but it does spread laterally towards the North/East corner. It is evident that vertical flame spread is much faster than horizontal flame spread. Much more detailed recounts of the process are provided by Dr Lane and Prof. Bisby's Phase One expert reports [4,5].



Figure 20: Screen shot taken from the video recovered from Mr KEBEDE's mobile phone [A14] at time stamp 01:05:57. This shows some material falling from the building beneath the left hand side of the window (as viewed from outside).

FIGURE 18: FIRST EVIDENCE OF FLAMES EXITING THE COMPARTMENT OF ORIGIN [2].

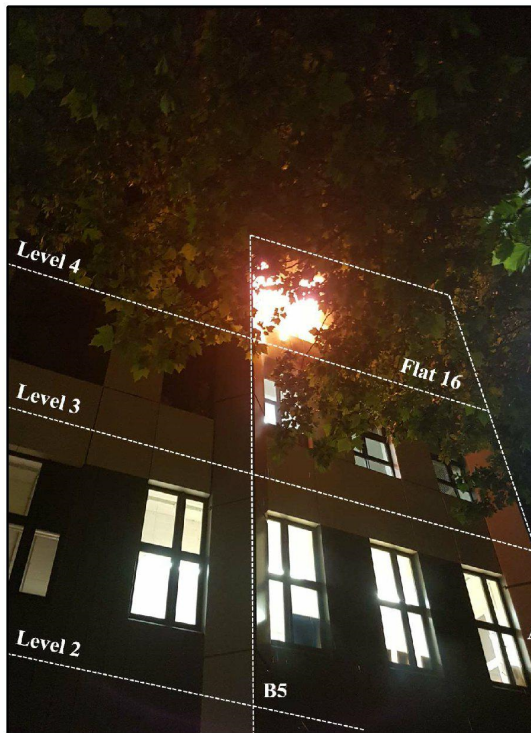


FIGURE 19: EARLIEST IMAGE OF EXTERNAL FIRE OBSERVED ON LEVEL 4, AT 01:14 ON 14 JUNE 2017 (MET00006589)

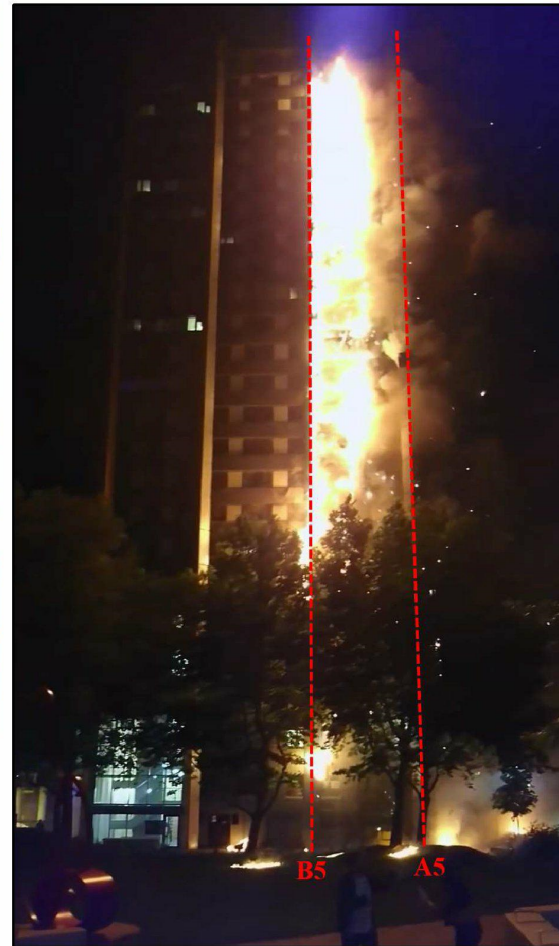


FIGURE 20: FIRE ON THE FULL HEIGHT EAST ELEVATION OF THE BUILDING ENVELOPE ON 14 JUNE 2017, ESTIMATED TIME 01:26 (COUNSEL TO CONFIRM TIME) ([HTTPS://WWW.YOUTUBE.COM/WATCH?V=6AYUZ5SNxZO](https://www.youtube.com/watch?v=6AYUZ5SNxZO))

4.2 VERTICAL FIRE SPREAD OVER ACP PANELS

Flame spread is controlled by the transfer of heat from the flame to the combustible material. This is a complex process, in particular for products such as Aluminium Composite Panels where spread requires breaching non-combustible layers such as aluminium. The literature on the physics of flame spread provides extensive data characterizing vertical and lateral flame spread which shows that vertical flame spread rates are generally at least ten times faster than lateral flame spread rates [23]. Furthermore, the bigger the burning zone, the faster the rate of spread of a vertical flame i.e. upward flame spread self-accelerates. In contrast, lateral spread does not accelerate unless external heat is provided. Most data on flame spread is associated to combustible materials with not much data available on composite systems such as Aluminium Composite Panels (ACP). There are few studies on this matter, with the most specific being that of Ogilvie [16]. Ogilvie confirms that vertical flame spread rates are more than three times the rates of lateral flame spread.

The most comprehensive review of external fires was produced by the NFPA [13]. This document describes briefly a significant number of fires occurring prior to 2014 but unfortunately provides very few details of each event. An independent review of international events involving external fires was conducted for the purpose of this report. This review shows that the most common scenario is that of a flame rapidly spreading upwards with very limited lateral flame spread. Figure 21 shows three examples, the Torch Building in Dubai, the Lacrosse Building in Melbourne and the Address Building in Dubai. With the exception of the Lacrosse fire, where a report was made public, there is not much reliable data on the characteristics of these events. Nevertheless, the available footage clearly shows that once the fire has spread to the top, it proceeds to decay and eventually extinguish. There are many reasons why this could happen. The main one is that the amount of fuel per unit area is small so the local duration of the fire is limited to a few minutes.

In most of these cases lateral flame spread was limited. This is to be expected because the amount of energy necessary to spread a flame (critical heat flux for ignition) over an ACP panel is significant. Common materials will not exceed a critical heat flux for ignition of 15 kW/m^2 [24], while ACP panels can commonly reach values as high as 18 kW/m^2 [16]. Lateral spread is controlled by radiative heat transfer from the flame to the unburnt material, with convection cooling the same area of material, thus the net heat flux provided by the flame is the difference between the two. Heating areas are very small because convective flows carry heat from the material towards the flame, limiting the preheating area (Figure 22 (a)). In contrast, in vertical flame spread, convection and conduction both heat the material, so not only is the heat flux to the unburned surface greater (the sum of the two), but it also heats a larger area. The larger the flame the larger the heated area and therefore the faster the spread (Figure 22 (b)). Therefore, as time progresses, vertical flame spread accelerates while lateral flame spread tends to have a constant velocity.

Literature review on past fire events in high-rise buildings involving vertical flame spread via external cladding shows a very similar behaviour in most cases. This literature includes official reports, media, video footage, and industry and academic papers. Quantified rates of vertical flame spread based on available evidence were developed and are presented in Figure 23. As can be seen from Figure 23, vertical flame spread for Grenfell Tower is among the lowest reported. Fire spread rates range from less than 1 m/min to approximately 20 m/min .

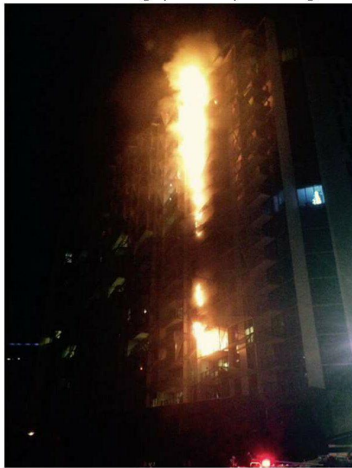
1628



(a) The Torch Building (Dubai) during the fire



(b) The Torch Building (Dubai) after the fire



(c) The Lacrosse Building (Melbourne) during the fire



(d) The Lacrosse Building (Melbourne) after the fire



(e) The Address Building (Dubai) during the fire



(f) The Address Building (Dubai) after the fire

1629

1630

FIGURE 21: EXAMPLES OF VERTICAL FIRE PROPAGATION WHERE THERE WAS MINOR HORIZONTAL FIRE SPREAD.

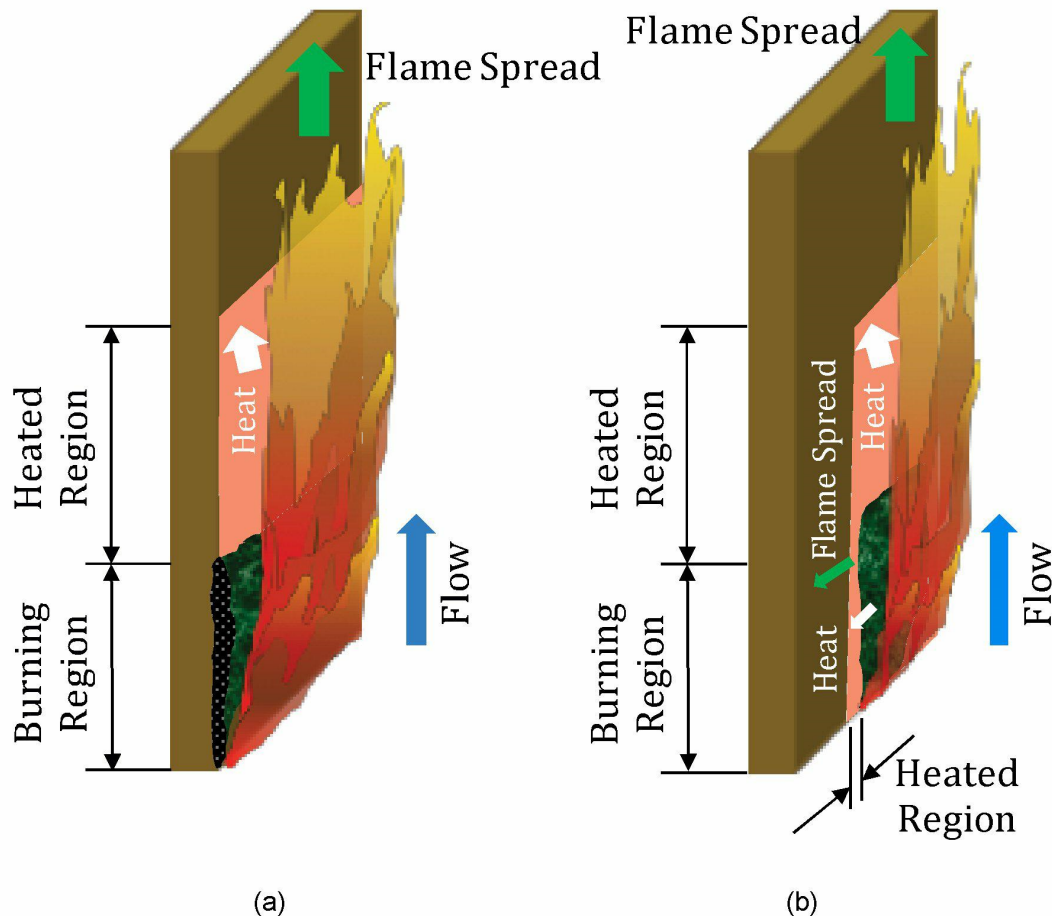


FIGURE 22: SCHEMATICS OF LATERAL AND VERTICAL FLAME SPREAD. (a) SHOWS A FLAME SPREADING ONLY UPWARDS AND COVERING THE ENTIRE WIDTH OF A MATERIAL. THE AREA IN GREEN (BURNING REGION) PRODUCES FUEL AND IT DEGRADE IN-DEPTH (BLACK AREA). THE FUEL FEEDS THE FLAME THAT IS LONGER THAN THE BURNING AREA. THEREFORE, THERE IS AN AREA THAT IS TO BE HEATED (HEATED REGION). GIVEN THAT THE FLOW AND THE FLAME SPREAD ARE GOING IN THE SAME DIRECTION, THE AMOUNT OF HEAT LANDING IN THE HEATED REGION IS LARGE AND THE SIZE OF THE HEATED REGION IS LARGE. THE RESULT IS ROBUST AND FAST FLAME SPREAD VERTICALLY. (b) SHOWS THE CASE WHERE THE FLAME DOES NOT COVER THE ENTIRE WITH OF THE MATERIAL (GREEN), IN THIS CASE IT CAN CONTINUE TO SPREAD VERTICALLY AS PER FIGURE (a) NEVERTHELESS IT CAN ALSO SPREAD HORIZONTALLY. HORIZONTAL FLAME SPREAD WILL NOT BE IN THE SAME DIRECTION OF THE FLOW, SO MOST OF THE HEAT WILL BE CARRIED UPWARDS, THEREFORE THE AMOUNT OF HEAT REACHING THE HEATED REGION IS VERY SMALL. THE HORIZONTAL PROJECTION OF THE FLAME IS ALMOST OF THE SAME SIZE AS THE BURNING REGION THEREFORE THE HEATED REGION ITSELF IS VERY SMALL. THE RESULT IS THAT HORIZONTAL FLAME SPREAD WILL BE WEAK AND SLOW.

The Grenfell Tower cladding system was composed of multiple components, these are described in detail in [4] and [5] so they will not be described here. This system included multiple combustible materials (ex. Polyisocyanurate insulation (PIR), polyethylene infill for the ACP panels, EPDM Synthetic Rubber Membrane, etc.). All these materials would have sustained combustion. The polyethylene infill was placed between two aluminium plates that will melt in the range 580 - 650°C. Thus, in the presence of a significant flame the aluminium would have represented no protection to the polyethylene. Flames are typically between 600°C-800°C, thus are hotter than the melting

temperature of aluminium. Furthermore, polyethylene is a thermoplastic, thus will melt and drip. This can happen before or after ignition. In the case of polyisocyanurate, this material is low density closed pore insulation that will not melt. Instead it will char and stay in place. Polyisocyanurate has been studied in detail by Hidalgo *et al* [25]. Polyisocyanurate foams when heated and releases very little heat per unit area (less than 60 kW/m^2). In the absence of any external heating it will generally extinguish leaving approximately 60% of its mass as residue. When heated by more than 40 kW/m^2 it will generally be consumed fully [25].

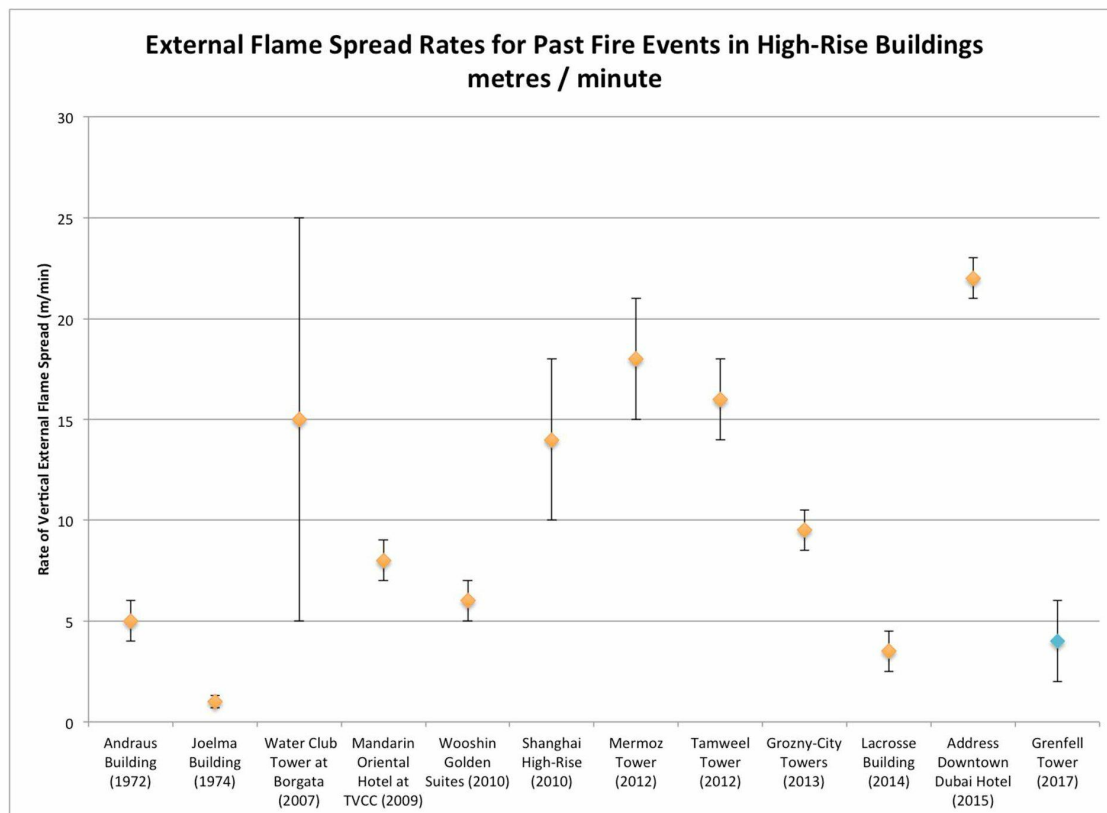


FIGURE 23: EXTERNAL FLAME SPREAD RATES FOR PAST FIRE EVENTS, COMPARED TO GRENFELL TOWER. NOT INCLUDED IN THIS PLOT IS A RESIDENTIAL BUILDING FIRE IN BAKU, AZERBAIJAN IN 2015, WHICH HAD AN UNEXPLAINED RATE OF FLAME SPREAD OF $\sim 110 \text{ m / min}$. THIS FIGURE PRESENT AVERAGE VALUES FOR COMPARISON PURPOSES, NEVERTHELESS IT IS RECOGNIZED (AS INDICATED ABOVE) THAT THE FIRE SPREAD RATE WILL ACCELERATE. VALUES FOR GREFELL TOWER AND ADDRESS DOWNTOWN DUBAI HOTEL SHOW CONSISTENCY WITH THOSE REPORTED IN (FIGURE 97 [5]).

Figure 24 shows the different levels of damage of the cladding system. In the bottom and bottom right corner, sectors of the cladding appear undamaged, with the aluminium plates intact. Other sectors towards the middle of the photograph show the melted aluminium with the fully consumed insulation (centre of the image). Other sectors show the charred insulation which indicates that heat fluxes were not sufficiently high to consume the char. Finally, other sectors show the distinctive yellow colour of

the unburnt PIR. The infill is extracted from Hidalgo *et al* [25] for illustration. This shows a sample exposed to 25 kW/m^2 for a period of 22.5 minutes. The range of conditions observed from a single image (In Figure 24) demonstrates that the heat exposure was not homogeneous, with areas of intense local heating and areas of mild heating. These same observations can be seen in multiple locations on the building after the fire.

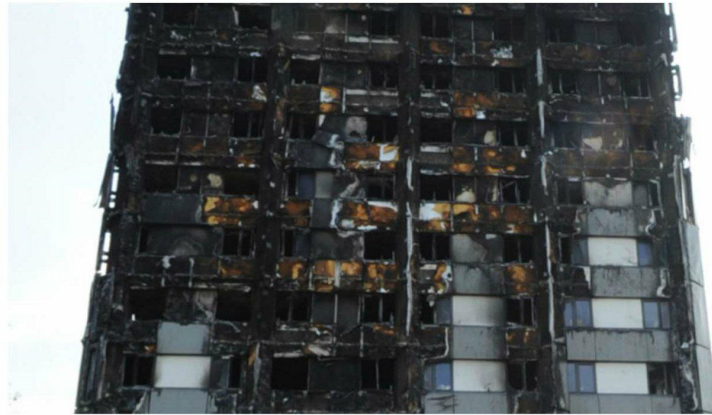
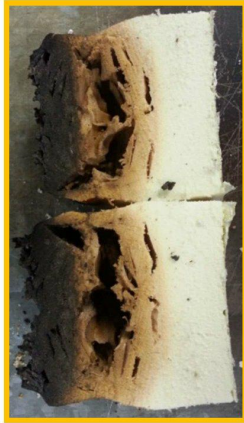


FIGURE 24: IMAGE OF THE GRENFELL TOWER AFTER THE FIRE SHOWING DIFFERENT LEVELS OF DAMAGE IN ONE SINGLE LOCATION. INFILL PHOTOGRAPH FROM HIDALGO ET AL [25] SHOWING THE DIFFERENT LEVELS OF DEGRADATION OF PIR.

It is less common for fires to spread laterally. In most cases, once the fire has reached the upper parts of the building, the lower areas are progressing towards extinction because most of the fuel has been either consumed or melted and dropped downwards. It is common to see burning debris descend but the debris is generally localized within the area of the fire.



FIGURE 25: SULAFU TOWER (DUBAI) DURING THE FIRE. LATERAL PROPAGATION EXTENDED TO ALMOST HALF OF THE BUILDING.

There are a few exceptions where the fire has propagated laterally fully or partially involving the building (Figure 25). There is very limited information about the construction details of any of these buildings, therefore it is not possible to establish what enabled the horizontal flame spread.

4.3 CONTROLLING MECHANISMS OF FLAME SPREAD

Vertical flame spread over combustible materials has been studied for decades [26] and the mechanisms controlling the different modes of flame spread have been described in great detail. The effect of flow velocity, external heat fluxes, material properties, etc. have been analysed extensively. Adequate models for simple scenarios such as vertical spread or lateral spread over a flat plate have also been studied. Less attention has been given to the spread of flames within cavities [12]. Nevertheless, it has been found that the width of the cavity (“W” in Figure 26) plays a fundamental role in the rate of flame spread. At the extremes, if “W” is large, radiative feedback and buoyantly driven chimney effects disappear with flames spreading at similar rates, as in the case of an exposed surface. Conversely, if “W” is very small, thermal expansion of the gases block the flow and the flames cease to spread internally remaining outside the gap. This information provides valuable insight and can potentially be used to explain some of the visual observations of the fire spread process during the Grenfell Tower fire [4, 5]. Accelerated spread can be explained by the presence of open vertical channels, inducing chimney effects associated to their width (“W”) and also by preferential burning of polyethylene over PIR insulation, based on their material properties. Nevertheless, the adequacy of these interpretations is limited to very simple scenarios and requires caution.

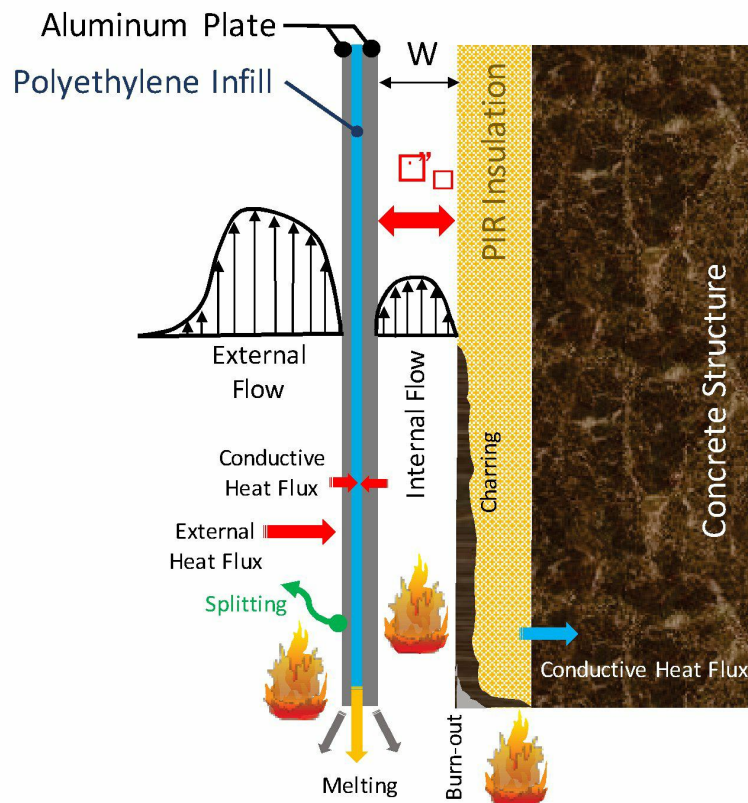


FIGURE 26: PROCESSES CONTROLLING FLAME SPREAD.

It is often the case that when construction systems are developed, little attention is given to the extreme complexity introduced. Figure 26 shows a very simplified schematic of the different processes

occurring during the spread of a flame within a simplified version of the system used in Grenfell Tower. In a system of such complexity, many other processes are introduced beyond simple effects such as the role of “W” (i.e. the cavity width). The low melting temperature and high thermal conductivity of aluminium results in complex heat transfer from external flames into the infill. Furthermore, melting of the aluminium is possible, so the loss of protection needs to be accounted for. The polyethylene infill will also melt at low temperatures, while the temperature gradients between the inside and the outside will result in differential deformations of the plates. This can lead to splitting of the plates and exposure of the polyethylene [16]. Inside the cavity, the PIR will pyrolyze, char, burn but also potentially burn-out. The PIR has a very low thermal inertia [5] which favours a fast flame spread rate, nevertheless its charring potential results in small fuel production and therefore short flame lengths. Charring, therefore, has a detrimental effect on flame spread. The outcome of these two competing effects is determined by the radiative feedback from the ACP, thus the way the ACP burns defines the way the PIR will spread a flame. Furthermore, the way the PIR burns will then affect the rate at which the ACP will degrade, melt and burn. Faster degradation induces further melting and thus might reduce spread rates but increase the rate at which molten debris falls. The interactions between the two materials are therefore difficult to uncouple.

These are only a few of the complexities introduced in these systems. When the systems are applied in construction, a multiplicity of other complexities are introduced (cavity barriers, complex geometries, other materials, intumescent sealants, etc.). The level of complexity is such that a very careful analysis is necessary to establish the fire performance of such a system. A comprehensive treatment of all complexities is beyond the objectives of this section, nevertheless, some of these complexities are introduced to highlight the need for a different form of thinking.

Tests such as BS 8414 [27] provide a single scenario deemed consistent with an external fire, a very limited number of measurements and a very simple failure criterion. The combination of these three characteristics does not provide a sufficiently comprehensive assessment of performance. Many details can be hidden within the results of the test and therefore great caution needs to be exercised when interpreting such tests. In particular, it is essential to recognize the limitations of the failure criteria and the complexities associated to its extrapolation to real systems.

Observation of the images associated with the Grenfell Tower fire can establish patterns of behaviour specific to this incident. These patterns of behaviour are a combination of multiple processes interacting with each other (Figure 26 and many more) and leading to specific observations. These observations are by no means universal, they are intimately associated with the conditions of the building and this specific event, and should only be extrapolated with great care.

A critical aspect that is missed by BS 8414 [27] and observations is the burn-out of the insulation material. As explained in previous sections, the residual PIR has different levels of degradation, thus it burns-out at different stages as a function of the heat flux that is fed back to the material. All other components of the cladding either melt or have a small mass per unit area, thus their burning time is very short. The insulation has the potential to burn for a much longer time period. The duration of localized burning will be critical when defining the capacity of these fire to break back into the building. Observations focus on visible flames, but these can over emphasize the burning of the rain-screen. The fire source, the focus on flame spread and duration of the test in BS 8414 [27] all mask the role of the insulation and over emphasize the role of the rain-screen. None address the burn-out times and their role on sustaining localized burning.

It is important to emphasize that a significant reason for the numerous external fires that have occurred in the last few years is the incapacity of these traditional approaches to establish the performance of these complex systems (assessments and/or tests). The information that can be extracted from current tests and observations of events is very limited. This information is of a quantity and quality which is inconsistent with the complexity of the systems. If these performance assessment methodologies are to be used, then the façade systems need to be drastically simplified. If systems of this complexity are to remain, so as to fulfil other functions, then a more comprehensive methodology of testing and a very different approach to performance assessment needs to be implemented.

As indicated in Dr Lane's Phase One Expert Report [4] in section 2.29.2 and 2.29.3, the introduction of these complex façade systems results in "complex and confusing" National and European reaction to fire tests. This results from the inadequate use and adaptation of tests that were never intended to define what "adequate" flame spread should be. While all these tests provide valuable information, this information requires interpretation beyond what can be issued by means of guidance. Appendix F (Section 1.1) of Dr Lane's report [4] illustrates the resulting complexity of the different accepted testing regimes. It is important to note that the testing options are so extensive that materials well known to challenge the concept of "adequate" flame spread can find a path to be routinely used in high rise buildings.

There is fear that a comprehensive testing methodology will be impractical and expensive and that simple failure criteria with standardized tests is the most practical approach to performance assessment. In my view, this is an incorrect way of thinking. A comprehensive methodology establishes the specific processes that matter, provides the information that is necessary and allows for establishing the robustness of the system. Gathering this information might only require simple and fast experimentation. What will be unavoidable is a comprehensive analysis that can only be conducted by a highly proficient professional.

No detailed differentiation of the mechanisms controlling flame spread will be proposed here. A detailed analysis of BS 8414 [27] to establish its value and limitations is proposed for Phase Two. The development of a testing protocol that will allow for comprehensively determining the influence that each material, components and geometry had on the spread of fire on the Grenfell Tower will also be a fundamental aspect of Phase Two. It is my firm view that only on the basis of this new approach can recommendations for future designs be made.

4.4 EFFECT ON TENABILITY AND STRUCTURAL STABILITY

At the time of writing, available evidence and expert reports point to at least three internal fires igniting as a result of the initial vertical propagation, within the timeframe of Stage 2. These fires occurred on the 5th, 12th and 22nd floor, in flats directly above the flat of fire origin, and were ignited at approx. 01:18, 01:24, and 01:28 respectively. This fire re-entry is discussed in detail in the following section (Section 5).

Towards the end of Stage 2, calls to emergency services rapidly began to increase reporting inability of residents to evacuate their flats due to smoke build-up in communal lobbies, both on and around

1796 the floors with known fires. This indicates a rapid failure of horizontal and potentially also vertical
1797 compartmentalization within the tower.

1798 While tenability was beginning to be compromised locally, this time period (01:15 – 01:30) falls within
1799 the period of peak egress rate of occupants from the tower according to Table D in Dr Lane’s Phase 1
1800 Expert Report [4], indicating that the egress stair was still passable and smoke propagation was
1801 confined to communal lobbies.

1802 4.5 COMPLIANCE ISSUES AFFECTING THE CHARACTERISTICS OF 1803 STAGE TWO

1804 The main issue of compliance stems from Section 12 of ADB and Appendix A of ADB (covered in Section
1805 F1.1.5 [4]) where it is stated at paragraph 1:

1806 “In such cases the material, product or structure should:

- 1807 a. Be in accordance with a specification or design which has been shown by test to be capable
1808 of meeting that performance; or
1809 **Note:** For this purpose, laboratories accredited by the United Kingdom Accreditation Service
1810 (UKAS) for conducting the relevant tests would be expected to have the necessary expertise.
- 1811 b. have been assessed from test evidence against appropriate standards, or by using relevant
1812 designs guides, as meeting that performance; or
1813 **Note:** For this purpose, laboratories accredited by UKAS for conducting the relevant tests and
1814 suitably qualified fire safety engineers might be expected to have the necessary expertise.
1815 For materials/products where European standards or approvals are not yet available and for
1816 a transition period after they become available, British standards may continue to be used.
1817 Any body notified to the UK Government by the Government of another member state of the
1818 European Union as capable of assessing such materials/products against the relevant British
1819 standards may also be expected to have the necessary expertise. Where European
1820 material/products standards or approvals are available, any body notified to the European
1821 Commission as competent to assess such materials or products against the relevant European
1822 standards or technical approval can be considered to have the appropriate expertise.
- 1823 c. where tables of notional performance are included in this document, conform with an
1824 appropriate specification given in these tables; or ...”

1825 As the above extract from Appendix A of ADB indicates, there are three clear paths towards
1826 acceptance of a material or product; in section (a) performance is established “by test,” in section (b)
1827 performance is established by “test evidence” against “appropriate standards” or “design guides” and
1828 in section (c) by means of tables of notional performance.

1829 The performance criteria specified in Section 12.5 (ADB) [11] states: “The external walls of the building
1830 shall adequately resist the spread of fire over the walls and from one building to another.” As
1831 explained in Sections 2.3 and 2.4 of this report, for a building like Grenfell Tower the criteria of
1832 “adequately resist” is intimately linked to the fire safety strategy, thus a material or product to be
1833 used needs to be analysed in conjunction with the fire safety strategy and the building itself. Analysis
1834 of the material separate to the building will not guarantee the performance of the fire safety strategy.
1835 This invalidates paths (a) and (c) because both paths focus on the material/product and do not include

statements about the design. Path (b) requires performance assessment “from test evidence against appropriate standards, or by using relevant designs guides” and as such remains as the single performance assessment route. Test evidence is to be provided by “laboratories accredited by UKAS for conducting the relevant tests” and used as evidence by “suitably qualified fire safety engineers” who “might be expected to have the necessary expertise.”

Path (b) is not explicit on what are the “relevant design guides,” furthermore when it comes to competence the vague terms “suitably” and “might” are used. Given that this is the only path to compliance, this performance assessment is of critical importance to the integrity of the fire safety strategy, and given that the consequences of inadequate performance are enormous; it is not acceptable to treat the problem in this manner. As indicated in Section 4.3 this matter is of a level of complexity that is not suitable for design guidelines, and instead requires a competent designer. A competent designer has to be properly qualified and assessed and it is not acceptable to treat competence in such a vague manner on a matter of such importance to safety. To my knowledge, a clear definition of necessary competence is currently not available and therefore this is a matter of critical importance that needs to be explored in Phase Two.

4.6 UNDERSTANDING THE RELATIONSHIP BETWEEN COMPLIANCE, PERFORMANCE AND QUALITY

The concepts of compliance, performance and quality should be related. One potential path to guarantee adequate performance and adequate quality should be compliance with existing building regulations and guidance. Other mechanisms, such as explicit performance assessment, are not excluded in Building Regulations (Section: Use of Guidance – The Approved Documents, paragraph 3 (ADB)).

In a system where compliance is the means of establishing adequate performance and adequate quality, it is necessary to introduce a process of approval. An approvals process seeks to evaluate compliance by establishing that the performance and quality criteria defined by Building Regulations and guidance are “complied” with. Approval will therefore, indirectly, establish adequate performance and adequate quality.

It is important to note that quality is only mentioned in ADB in matters pertaining to detection systems (Section 1.23, Section 1.37 and Appendix E (ADB)). In matters pertaining to functional requirement B4, only performance is discussed and it is defined as a function of criteria specified by means of standard tests (e.g. BS 476 Parts 4, 6, 7, 11, etc.), other guidance documents (BR 135), Council Directives (e.g. Council Directive 89/106/EEC, etc.), European Standards, etc. These criteria shall be used within the context of the three possible paths defined in Section 12 of ADB which are presented in the previous section.

In the case of the Grenfell Tower façade systems, it was established that path (b), which requires performance assessment “from test evidence against appropriate standards, or by using relevant designs guides” is the single path to compliance (Section 12 of ADB). Dr Lane in her Phase One expert report [4] states that: “2.29.21 I have concluded in Appendix D that the legal requirement is to demonstrate compliance with the functional requirement of the Building regulations 2010.” In the

1875 case of the façade system this is functional requirement B4. (1) “adequately resist the spread of fire”
1876 (ADB).

1877 Section 4.3 of this report describes the complexity of these façade systems and concludes that these
1878 systems are of such complexity that the direct results from any of the relevant tests are not sufficient.
1879 This is consistent with path (b) as specified by ADB and therefore this is the only path to compliance.

1880 The relevant standard testing methodologies are discussed in detail in Appendix F of Dr. Lane’s Phase
1881 One expert report [4]. Those of direct relevance are BS 476 (parts 4, 6, 7 and 11). These methods
1882 address combustibility (part 4), fire propagation (part 6), surface flame of spread (part 7) and heat
1883 emission (part 11). All variables are of great relevance to the spread of a fire over a façade system of
1884 this nature even if they are not required by ADB (Table A7).

1885 When following “path (b)” (ADB), “evidence” from these or other tests is to be used by “suitably
1886 qualified fire safety engineers” to establish if the performance of the system meets the functionality
1887 requirement B4. (1). The physical relationships that govern the spread of flame over façade systems
1888 of this nature are of extreme complexity (Section 4.3 of this report). In contrast, the tests are very
1889 simple, perform very basic measurements and none of them, by itself, incorporates all relevant
1890 features. Thus, the competency of the qualified fire safety engineer is of paramount importance. Any
1891 approval process attempting to establish “compliance” should therefore have focused on the
1892 performance analysis presented by a qualified fire safety engineer and on the qualifications of such a
1893 professional.

1894 Instead, in Dr. Lane’s Phase One expert report (Section 2) [4] it is stated:

1895 “2.19.2 I have found no evidence yet that any member of the design team or the construction team
1896 ascertained the fire performance of the rainscreen cladding system materials, nor understood how
1897 the assembly performed in fire. I have found no evidence that Building control were either informed
1898 or understood how the assembly would perform in a fire. Further, I have found no evidence that the
1899 TMO risk assessment recorded the performance of the rainscreen cladding system, nor have I found
1900 evidence that the LFB risk assessment recorded the fire performance of the rainscreen cladding
1901 system. I await further evidence on these matters, which I will explore in my Phase 2 report.”

1902 Furthermore, and as an example, Appendix E of Dr. Lane’s report [4] discusses the available testing
1903 evidence on relevant Celotex products. Here, she provides assessments of non-compliance (e.g. Table
1904 E.2) and concludes:

1905 “E2.3.4 I therefore conclude from my comparison that there are multiple significant differences
1906 between the rainscreen system tested in BS 8414-2:205 Test on Celotex RS500 insulated system with
1907 a ventilated Eternit Rainscreen produced by BRE Global on 01/08/2014, when compared with as built
1908 Grenfell Tower construction.

1909 E2.3.5 The most significant discrepancies are: ...

1910 ... E2.3.6 This test report therefore does not certify the as built Grenfell façade construction as
1911 compliant with ADB 2013, nor do I consider it to demonstrate compliance with the functional
1912 requirement B4 of the Building Regulations.”

1913 Dr. Lane presents further examples where other discrepancies between reported tests and the as built
 1914 Grenfell façade system were observed leading to the same conclusions. These are described in detail
 1915 in Appendix E [4].

1916 In my opinion, Dr. Lane's conclusions [4] are correct. In the complete absence of an analysis of the test
 1917 evidence, any differences between the as built and the tested systems will result in direct failure to
 1918 comply. Furthermore, any tests that are not exactly those required by ADB, cannot be used for
 1919 compliance purposes.

1920 Nevertheless, of even greater importance is the fact that, even if the tested system was identical to
 1921 the as built system, the tests conducted were exactly those required by the guidance, and that all
 1922 failure criteria for the tests were met, the Grenfell Tower façade system could have not been deemed
 1923 compliant without a detailed performance analysis and an appropriate assessment of the
 1924 qualifications of the fire safety engineer involved. These are requirements for "path (b)" (ADB).

1925 What is evidenced in this section is a misunderstanding of the process of compliance. The evidence
 1926 provided by Dr. Lane in her Phase One expert report (in particular Sections 2, Appendix E and Appendix
 1927 F) [4] demonstrates a culture by which "compliance" is trivialized by assuming that being "compliant"
 1928 only requires meeting the individual requirements stated in the Building Regulations and guidance. In
 1929 an approvals environment dominated by this culture, compliance simply becomes the process by
 1930 which approval is being sought/granted as a function of establishing that each individual criterion set
 1931 by standard tests, guidance documents, Council Directives, European Standards, etc. has been met.
 1932 Concepts such as adequate performance or adequate quality, which are the real objectives of Building
 1933 Regulations, are not proven to be attained by "compliance." The simple fact that ADB does not
 1934 introduce the term quality in section B4 is further demonstration of this culture. Finally, competency
 1935 of the engineer is completely disregarded.

1936 This section represents a brief presentation of the current culture of "compliance" and its non-existent
 1937 relationship with competency, performance or quality. It is of paramount importance to give further
 1938 attention to this matter in Phase Two.

1939 4.7 SUMMARY

- 1940 • Due to the comparative physical manifestations of buoyancy and air entrainment on heat feed
 1941 back to the unburned fuel, flames on a vertical surface will spread far more rapidly in the
 1942 upward direction than they will laterally.
- 1943 • This was observed at Grenfell Tower where, in approximately the first 15 minutes following
 1944 the establishment of flames on the exterior of the building, the flame spread rapidly from
 1945 Level 4 to the top of the building, while in the same period only spreading laterally a matter
 1946 of meters to the North.
- 1947 • The rate of upward flame spread observed was not unusual when placed in the context of
 1948 other historical events of this nature. In fact, at approximately 4m/minute it was one of the
 1949 slowest upward propagating examples.
- 1950 • The flames can be seen to take hold on the outside of the ACP panels from the very early
 1951 stages of vertical flame spread. Any non-conformity of cavity barriers or other detailing would

1952 therefore have not significantly affected the rate of vertical spread once the fire was
 1953 established on the exterior of the building.

- 1954 • As detailed in the following section, the initial vertical spread ignited a kitchen fire directly
 1955 above Flat 16 on Level 5.
- 1956 • Towards the end of this stage, a fire is ignited in Flat 196, Level 22. This fire apparently resulted
 1957 in reports of smoke blocking the communal corridor on this level however this is believed to
 1958 have happened later, probably in Stage Three.
- 1959 • Given the continued evacuation of occupants, the stairwell is still presumed to be tenable, at
 1960 least in parts, for the duration of this second stage of the fire. It is not known however which
 1961 floors in the building the evacuating occupants originated from. It can therefore not be
 1962 discounted that parts of the stairwell may have experienced smoke infiltration.
- 1963 • The vast majority of the heat produced by the combustion of the cladding will be lost in the
 1964 smoke plume or absorbed by the unburned cladding ahead of the flame front and therefore
 1965 will not have reached the load bearing structure of the tower. The structure is not considered
 1966 to be at any risk during this stage of the fire.
- 1967 • Different details in the façade system (materials, geometry, cavity barriers, etc.) seem to
 1968 impact in different ways on the rate of flame spread [4,5]. Test conducted after the Grenfell
 1969 Tower fire [4,5] seem to provide further information. The complexity of this façade system is
 1970 such that observations and tests such as BS8414 [27] do not provide sufficient information to
 1971 be able to understand these differences. The quantity and quality of the data is inconsistent
 1972 with the complexity of the problem. At Phase Two I will be suggesting a testing protocol that
 1973 will provide information that is more pertinent to the complexity of these systems. At this
 1974 stage, this Phase One Report will not reach any conclusions on what are the controlling
 1975 mechanisms for flame spread in this stage of the fire.
- 1976 • Compliance of the façade design relies on establishing if it can “adequately resist the spread
 1977 of fire.” The only path to compliance is performance assessment “from test evidence” used
 1978 by a competent engineer using “relevant designs guides.” The complexity and importance of
 1979 the façade system requires more than guides and therefore the reliance is fully on
 1980 competency. There is no clear definition of competency, therefore this is a matter that needs
 1981 to be studied with great attention in Phase Two.
- 1982 • The relationship between compliance, performance and quality is currently poorly
 1983 established. The means by which performance, quality and compliance for the Grenfell Tower
 1984 façade system were assessed are deeply flawed. The current culture of “compliance” needs
 1985 to be revisited in great detail in Phase Two.

1986 5 STAGE THREE: LATERAL FIRE SPREAD AND INTERNAL 1987 MIGRATION

1988 5.1 LATERAL MIGRATION OF THE EXTERNAL FIRE

1989 The Grenfell Tower fire is unusual in that horizontal flame spread enveloped the entirety of the
1990 building. The fires spread laterally around the building in less than three hours. It is clear that there
1991 are multiple pathways for the fire to spread through the façade system [4, 5], nevertheless, in my
1992 opinion, none of these explain the lateral propagation of the fire. As can be seen from the earlier
1993 footage of the fire, there is very limited lateral spread across the face of the building. Dr Lane [4] and
1994 Prof. Bisby [5] present in their Phase One expert reports, ample evidence of many pathways to lateral
1995 spread and specific photographic evidence is presented for each of these pathways ,but, nevertheless,
1996 no dominant pathway is conclusively established. Furthermore, video and photographic images do
1997 not seem to determine clear and consistent propagation characteristics.

1998 5.1.1 MECHANISMS DRIVING LATERAL FLAME SPREAD

1999 This section serves as a complement to Dr Lane [4] and Prof. Bisby's [5] Phase One expert reports with
2000 the objective of adding further clarity to a mechanism of fire spread that is particular to Grenfell
2001 Tower. This is not intended to diminish the importance of other hypotheses (Section 6.3.4 [5]) nor to
2002 diminish the complexities associated with external spread over these type of façade systems (as
2003 indicated in Section 4.3 of this report).

2004 Figure 27 shows a different mechanism. The fire reaches the architectural crown of the building and
2005 this crown behaves as a preferred path for lateral propagation. Hot smoke plumes from fires lower
2006 down on the building façade will also contribute to lateral spread. The rising plume will widen with
2007 height and transfer heat over a greater width in the upper levels of the building. This hot smoke
2008 preheats upper sections of the cladding which facilitates later ignitions in these areas. Thus, the
2009 expanding smoke plumes would serve to accelerate lateral flame spread at the upper areas of the
2010 building.

2011 While this is clearly a factor that needs to be considered [5], it seems that a different process drives
2012 horizontal spread. In particular, it can be observed that lateral fire spread is more rapid over the
2013 architectural crown structure of the building than elsewhere.

2014 Figure 28 shows a view of the East façade where it can be clearly seen that the fire is propagating
2015 faster over the architectural crown structure. The following figure shows how debris from this fire
2016 starts to ignite the areas below. In the meantime, the fire continues to propagate through the
2017 architectural crown structure towards the South-East corner.

2018 By 02:16:41 (Figure 29) falling debris continues to spread the fire downwards while the flames now
2019 involve several floors underneath the architectural crown structure almost to the South-East corner.

2020 The final photograph of the sequence (Figure 30, 02:30:10) shows the fire turning the South-East
 2021 corner and starting its propagation over the architectural crown structure in the south face of the
 2022 building.



2023

2024 **FIGURE 27: EAST FAÇADE - BURNING DEBRIS GATHERING ON LEDGES BELOW FIRE AT ~LEVEL 18 (FLAT 151, 2:09:20)**



2025

2026 **FIGURE 28: EAST FAÇADE – SIGNIFICANT DOWNWARD FIRE SPREADS IN 6 MINUTES (2:16:14)**



2027

2028 Figure 29: Flaming falling debris have ignited 3 further floors downwards (02:16:41)



2029

2030 Figure 30: Fire spreading to south façade from east façade architectural crown (2:30:10)

It is important to note that the lateral spread of the flames through the architectural crown structure is faster than the lateral propagation through the façade system in the building. The characteristics of the architectural crown structure have been described in detail by Prof. Bisby in his Phase One expert report [5]. As indicated by Prof. Bisby [5], the characteristics of the façade system in this region of the building will clearly allow for faster propagation (Hypothesis E5, lines 858-864).

Finally, simple calculations show that the average lateral fire spread in the architectural crown structure remains less than 0.5 m/min which is about one eighth of typical vertical fire spread rates.

As debris falls from burning areas, they will accumulate on window ledges or indeed on any available horizontal surface, igniting new localised fires. Figure 31 shows an example of such a spread mechanism. Debris will ignite a fire which will then propagate upwards to meet with other fires thereby covering completely that sector of the building. This appears to be the governing mechanism for lateral spread observed at Grenfell Tower.



FIGURE 31: FIRE VISIBLE ON FAÇADE BELOW FIRE ON EAST ELEVATION

This mechanism (lateral flame spread over the architectural crown of a building) has been observed in previous fires, in particular in the Monte Carlo Casino & Hotel Fire in Las Vegas on January 25th, 2008 (Figure 32). At the Monte Carlo Casino & Hotel, the polystyrene and polyurethane portions of the exterior insulation and finishing panels (EIFS panels) and trim burned along the building's parapet. Molten material ran down the exterior edge of the hotel, starting fires in other EIFS panels. As the fire spread from the centre of the west and south wings of the hotel, it also began to burn downward, impinging the windows of the suites on the 32nd floor. The heat caused several windows on the 32nd floor to fail and flames spread into the building.

This mechanism was also recently observed in a fire at the Taksim İlk Yardim Hospital in Istanbul, Turkey on April 5th, 2018 (Figure 33). Local news coverage reported the fire started on the roof of the hospital and spread downwards and laterally to incorporate the external façade of the building. The fire did not spread into the interior of the building, however there was smoke spread internally. Patients were evacuated and no casualties have been reported to date from the event.

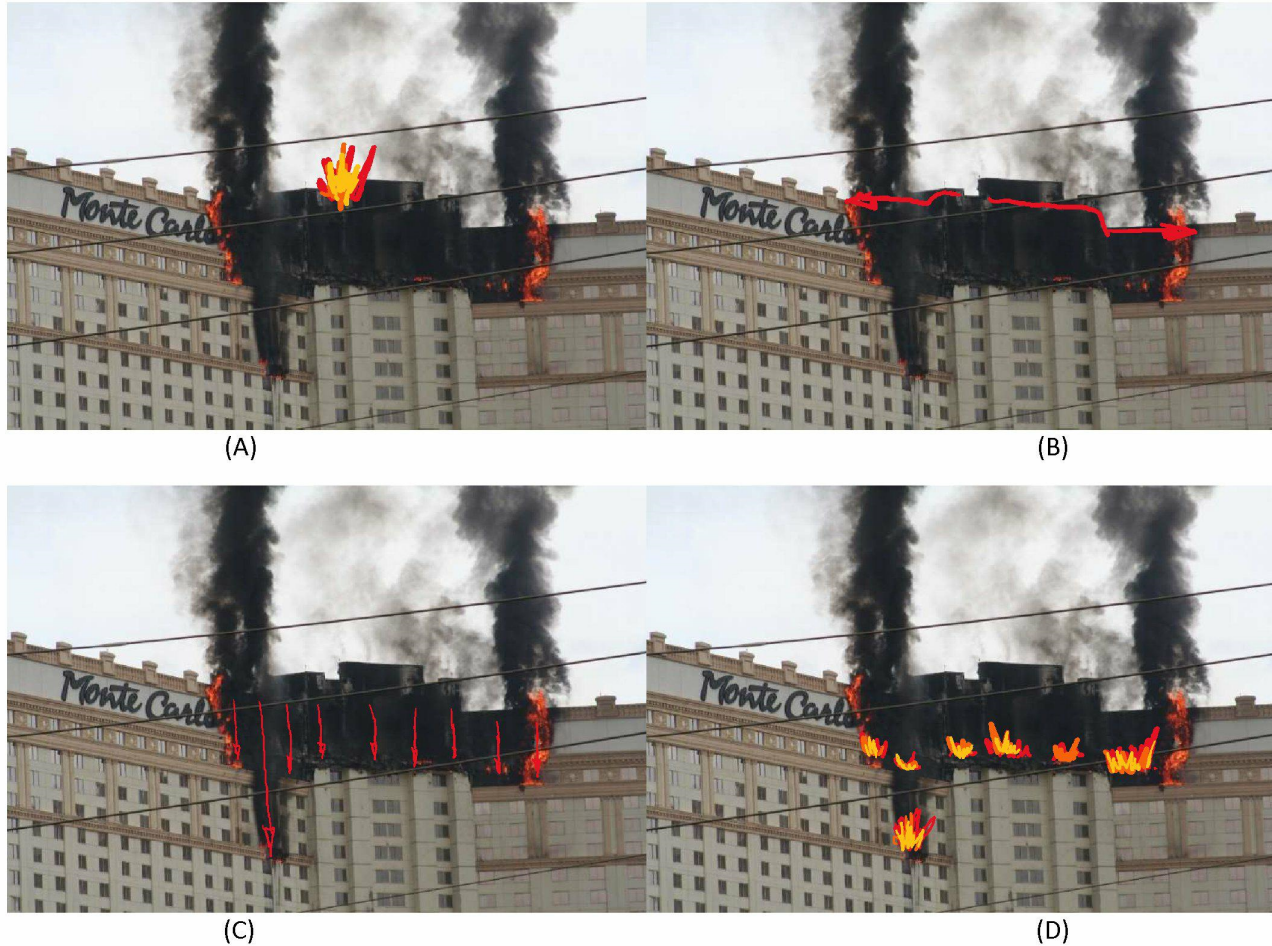


FIGURE 32: MONTE CARLO CASINO & HOTEL FIRE, LAS VEGAS, JANUARY 25TH, 2008. (A) SHOWS THE EXTERNAL FIRE SPREAD FROM THE INITIAL IGNITION AT THE ROOF LEVEL OF THE BUILDING. (B) THE FIRE SPREADS Laterally ACROSS THE PARAPET. (C) Molten burning material drips down the façade and builds up on lower level parapets. (D) Build-up of molten material ignites fresh fires which break in through windows and results in further compartment fires.

2065

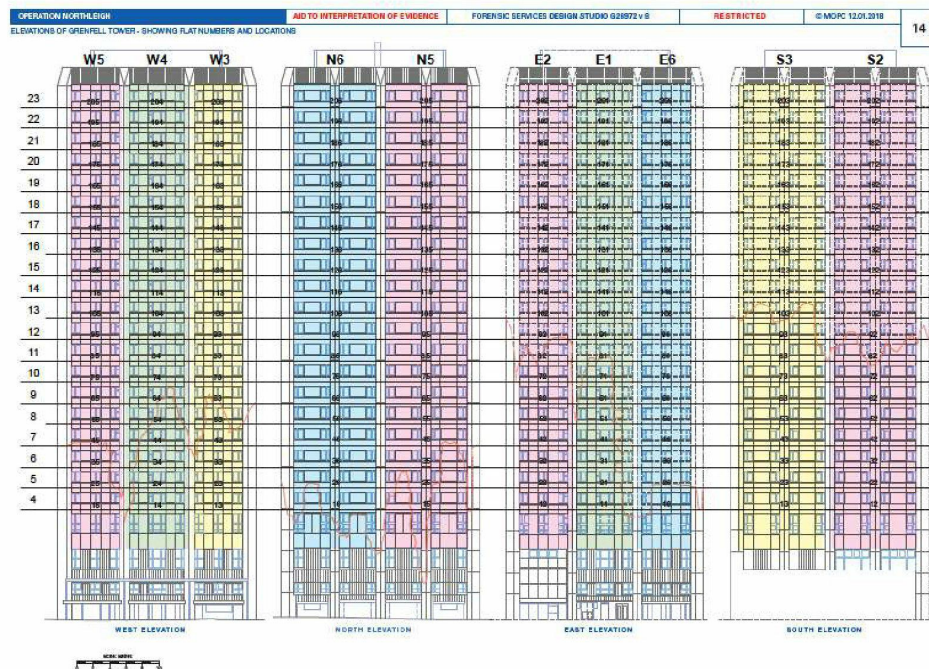


2066

2067 **FIGURE 33: STILL IMAGES FROM COGAN NEWS AGENCY COVERAGE OF THE TAKSIM ILK YARDIM HOSPITAL FIRE IN ISTANBUL,**
 2068 **TURKEY ON APRIL 5TH, 2018, SHOWING THE PROGRESSIVE DOWNWARD AND LATERAL SPREAD OF FLAMES**

2069 5.1.2 DETAILED ANALYSIS OF THE EXTERNAL SPREAD OF THE FIRE

2070 To understand the timeline of external fire spread it was necessary to analyse multiple images. This enabled
 2071 identification of the mechanisms by which fire spread around the building and confirmed a timeline of spread.
 2072 The building was divided in sectors as indicated in Figure 34 extracted from [MET00008024].



2073

2074 **FIGURE 34: THIS FIGURE WAS EXTRACTED FROM REFERENCE [MET00008024] AND INDICATES THE COORDINATES OF EACH**
 2075 **RESIDENTIAL UNIT. THE NOMENCLATURE STIPULATED IN THE FIGURE WILL BE USED FOR THE FIRE SPREAD ANALYSIS.**

2076

2077 In an effort to examine, floor by floor, external flame spread (both lateral and vertical), floor versus time plots
 2078 were created using time stamped facade elevation tower plan views that highlighted fire coverage, including
 2079 the public footage sourced from MET00008024. A series of steps were executed to estimate and visualize the
 2080 external flame spread across each facade.

2081 The first step involved plotting approximate fire coverage (i.e. highlighted markings) from 01:14 am local time
 2082 onward based on time stamped facade elevation tower plan views in MET00008024. For examples of this step,
 2083 see Appendix E Figure 82 - Figure 86, Figure 89, Figure 91 - Figure 93, and Figure 95 - Figure 112.

2084 The second step was to identify any space and time gaps (i.e. greater than 30 min) in the analysis. The north
 2085 elevation was the only facade where there were any such gaps. Public footage between 1:42 am and 3:07 am
 2086 on the north elevation was sourced from MET00008024 to help fill in these spatial and temporal data gaps
 2087 (Appendix E Figure 87).

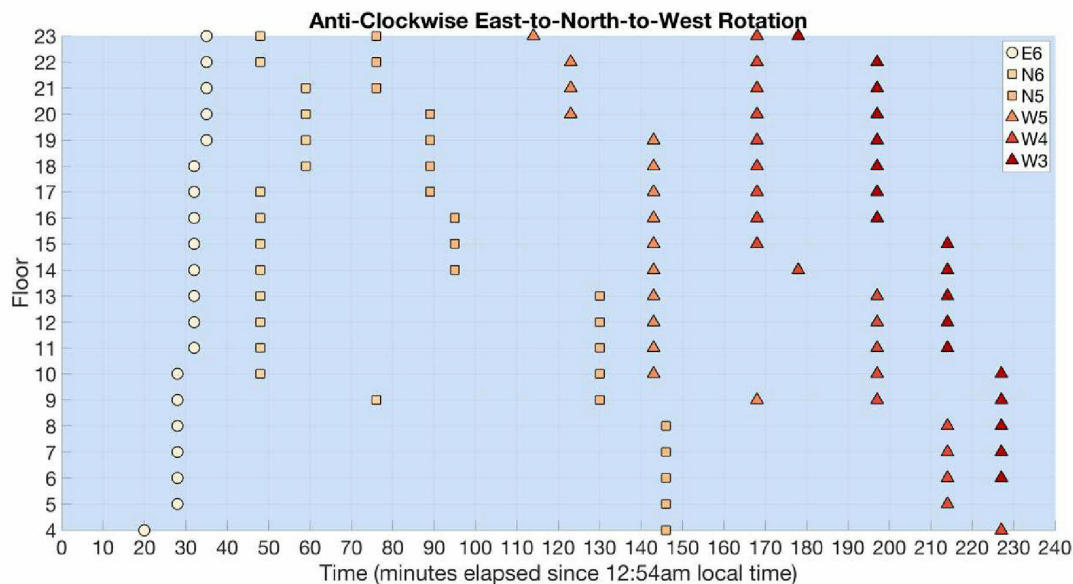
2088 To be able to discern some of the details of the images, it is necessary to process the images. In this case the
 2089 brightness of the flames hides details behind the fire and therefore it is necessary to illuminate the fire to see
 2090 what is behind. Well accepted professional tools exist in specialized commercial packages such as MATLAB.
 2091 For the purposes of this analysis MATLAB's image processing toolbox and a modified Spectral colorbar native
 2092 to ColorBrewer²³ was used to illuminate fire coverage. This toolbox was only deployed on three public images
 2093 of the north elevation (Appendix E Figure 88; Figure 90; and Figure 94).

2094 The resultant characterisation of the external fire spread is condensed into the plots in Figure 35. The plots
 2095 show spread to the north and south respectively from the initial external fire on the east façade. The key
 2096 indicates which of the sectors each data point refers to as established in Figure 34. A step by step guide through
 2097 the external evolution of the fire is presented in Appendix E.

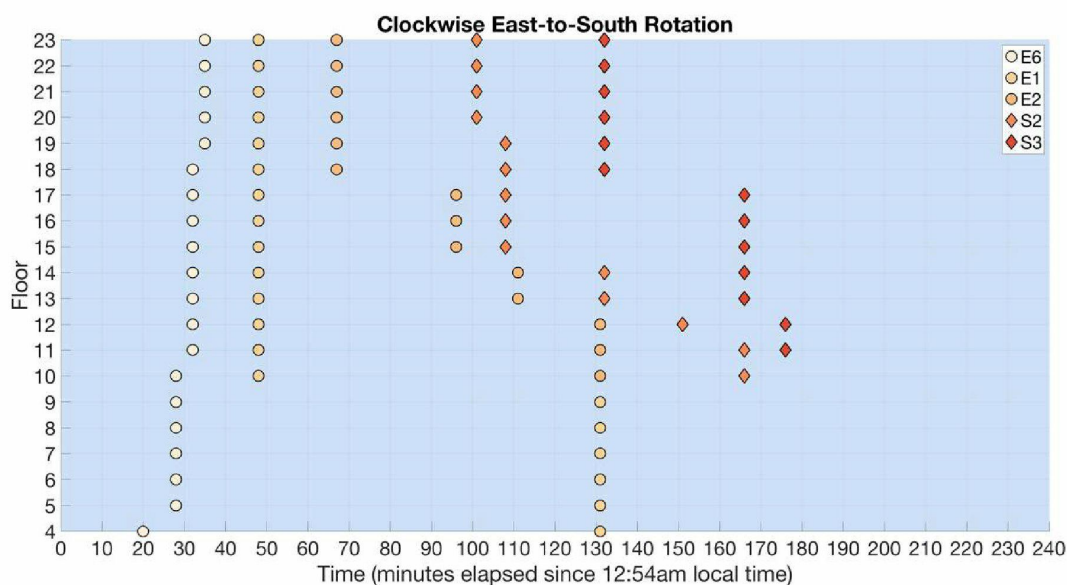
2098 The initial vertical line of markers, common to each plot, represents the initial vertical fire spread from the
 2099 initial point of ignition on the external façade. By following the subsequent markers for each sector, it is clear
 2100 that the initial ignition in each sector, beyond those immediately adjacent to the initial vertical spread, is at
 2101 the top of the building where lateral spread happens most rapidly. Subsequent ignition of each of these sectors
 2102 further down the building happens noticeably later in time.

2103 The plot also captures how spread down the façade happens in clusters of floors. This is due to the spread
 2104 mechanism identified above. The lowest marker identified represents the level at which flaming debris or
 2105 molten material has collected and resulted in a remote ignition. The data points representing floors above this
 2106 appear to be a result of upward flame spread from this remote ignition.

²³ <https://www.mathworks.com/matlabcentral/fileexchange/45208-colorbrewer--attractive-and-distinctive-colormaps>



2107



2108

2109 **FIGURE 35: PLOTS INDICATING PROGRESSION OF LATERAL SPREAD IN TIME FROM 12:54 AM. AN EXTENSIVE DIAGRAMMATIC**
 2110 **BREAKDOWN OF THESE CHARTS IS PROVIDED IN APPENDIX E.**

2111 5.2 INTERNAL PENETRATION

2112 The external flames established on the façade system encounter multiple paths of entry into the building. The
 2113 building envelope is designed to serve as a barrier for fires occurring in adjacent buildings (heat fluxes as high
 2114 as 12.6 kW/m^2), but not to withstand an external fire generated within the building (see Section 2.4). External
 2115 fires will result in very significant heat fluxes (as high as 120 kW/m^2) that will damage numerous components

2116 of the building, in particular the window systems. Mechanisms for re-entry via the window systems principally
2117 follow three paths:

- 2118 1. Failure of the window glazing
- 2119 2. Failure of kitchen extraction fans
- 2120 3. Failure of the uPVC window surrounds

2121 While mechanism 3 is discussed in detail in Section 3.4.4, mechanisms 1 and 2 are discussed here. This
2122 discussion is presented here only with the objective of providing examples of paths through which the fire re-
2123 entered the building and in order to explain how none of the components of the window system were
2124 designed to serve as a barrier to prevent the fire from re-entering the building. It is not the intention of this
2125 section to describe a preferred path of re-entry.

2126 Dr Lane's Phase One expert report (Section 9 [4]) also provides a detailed account of all the weakness of the
2127 window as designed and built. Any of these weaknesses would have accelerated the ingress of the flames back
2128 into the building (as shown by the multiple evidence and testimonies presented). While all these weaknesses
2129 are important, and in many cases, will appear to dominate the ingress process, they will not be further
2130 discussed here. Given that the windows could not have been designed to withstand the level of heating
2131 provided by an external fire, there cannot be any expectation that the performance of the window system
2132 would have prevented ingress of the fire to other units. The presentation here should be seen as
2133 complimentary to Dr Lane's descriptions [4].

2134 Following any one of these failures, if the flames are then in contact with other combustible materials in the
2135 interior of the unit, then an internal fire will occur that could progress in a manner consistent with any
2136 compartment fire.

2137 5.2.1 GLAZING FAILURE

2138 Ogilvie [16] summarizes the range of heat fluxes delivered by external flames as reported by different authors
2139 (Table 4). FM Global considers in their testing requirements that the range should be extended up to
2140 approximately 120 kW/m² [12]. While the range is very large, it is clear that the magnitude of potential heat
2141 fluxes is above the critical heat flux for ignition of almost all combustible materials [28]. In particular, it is above
2142 the critical heat flux for ignition of all combustible materials present in the façade of Grenfell Tower [5].
2143 Building design guidelines suggest that the external envelope of a building shall withstand 12.6 kW/m² (see
2144 Section 2.4).

2145 Glazing has been extensively studied and experimental data shows that all forms of glazing will fail between
2146 5-10 kW/m² in a period of exposure between 60-300 seconds [29]. The higher the heat flux, the shorter the
2147 failure time. Given the typical heat fluxes for external fires, it will be expected that once the windows become
2148 engulfed by flames the fire will find a path inwards.

2149

2150

2151

2152

| Author | Heat Flux Value (kW/m ²) |
|-------------------------------|--------------------------------------|
| Saito et al. | 25 |
| Mowrer and Williamson | 30 |
| Delichatsios et al. | 30 |
| Delichatsios and Delichatsios | 25 |
| Delichatsios and Chen | 25 |
| Grant and Drysdale | 20 |
| Anderson et al. | 35 |
| Kokkala et al. | 25 |
| Qian and Saito | 25 |
| Quintiere and Lee | 25 |
| Lee et al. | 60 |
| Markstein and de Ris | 50 |

2153

2154 **TABLE 4: TYPICAL VALUES REPORTED FOR HEAT FLUXES EMERGING FROM EXTERNAL FLAMES, TAKEN FROM [16] CITING**
2155 **[30,31,32,33]**

2156 5.2.2 KITCHEN EXTRACTION FAN FAILURE

2157 Based on actual photos taken after the fire, it is possible to identify different scenarios where the failure of
2158 the kitchen extraction fan occurred. An analysis of the damage patterns to different components in this part
2159 of the windows shows clearly the multiple routes for the passage of flames from the exterior of the building
2160 to the interior of the building.

2161 Figure 36 shows a scenario where the heat fluxes available have not been able to breach any of the
2162 components of the window i.e. flames have not penetrated through any component of the window. But the
2163 detailing of the window, as described by [4,5], does not provide an adequate barrier between the interior and
2164 the exterior of the building and thus smoke is observed to have entered through any of the existing gaps.

2165 Figure 37 shows a slightly higher level of heat insult. This time the fan, which appears to be the weakest
2166 component (to heat), has deformed and is beginning to fall from its casing. A greater amount of smoke is
2167 present in the interior of the unit but this has not resulted in the ignition of any of the combustible materials
2168 of the compartment. It is important to note that in this case, the window is open allowing for smoke to
2169 penetrate freely.

2170 In Figure 38 it can be observed that the fan has now failed leaving a circular opening on the panel at the
2171 location of the original placement of the fan. Smoke has not only penetrated through this opening but has also
2172 entered the compartment through gaps between the window frame and the window. Flames did not
2173 propagate to the interior of the unit.

2174 In the next sequence of images (Figure 39, Figure 40 and Figure 41) the fan has failed, the windows are open,
2175 the glazing has, in some cases, failed (in others not) and the fire has penetrated and damaged the unit. In all
2176 of these cases, the panel originally holding the fan is still in place.

2177 A similar scenario can be seen in Figure 43 where the kitchen and adjacent room are significantly damaged,
2178 but the extractor fan panel still remains in place. The window in the room adjacent to the kitchen is severely
2179 damaged including the frame.



2180

2181 Figure 36: Kitchen window Level 9, Flat 62



2182

2183 **FIGURE 37: KITCHEN WINDOW LEVEL 10, FLAT 71**



2184

2185 Figure 38: Kitchen Window level 5, Flat 25



2186

2187 Figure 39: Kitchen window, level 7, Flat 44



2188

2189 Figure 40: Kitchen window, Level 6, flat 31



2190

2191 **FIGURE 41: KITCHEN WINDOW, LEVEL 7, FLAT 43**



2192

2193 Figure 42: Kitchen window, level 8, flat 54

2194 Figure 43, Figure 44 and Figure 45 show examples where the extractor fan panel has failed and the adjacent
2195 rooms have suffered different levels of damage. In Figure 42 and Figure 43 the external flames have ignited
2196 some elements of the unit while in Figure 44 and Figure 45 the elements of the unit are intact while the linings
2197 of the unit have been damaged but with very minor signs of a fire. Different levels of damage can also be
2198 observed on the window. Different levels of charring can be observed on the uPVC covering the window side
2199 (Figure 44 and Figure 45) while in other cases the window side is undamaged.



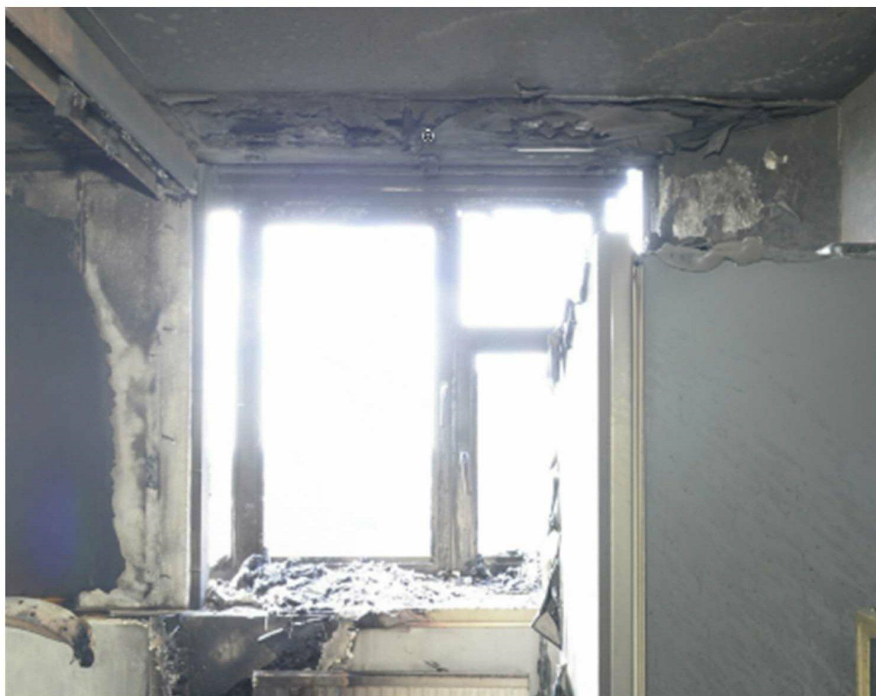
2200

2201 Figure 43: Kitchen window, Level 6, Flat 36



2202

2203 Figure 44: Kitchen window, Level 8, flat 53



2204

2205 Figure 45: Kitchen window, Level 12, flat 93

2206

2207 An important observation from Figure 42 and Figure 43 is the tall refrigerators located close to the windows.
2208 These refrigerators have similar characteristics to that which was present in the kitchen of Flat 16. The damage
2209 patterns seem to be quite similar, therefore it is important to explore the possibility that the external cladding
2210 fire outside the kitchen of Flat 16 might have been the cause of the damage to the tall refrigerator that was
2211 witnessed after the event. Given the information available, this is currently not possible to verify.

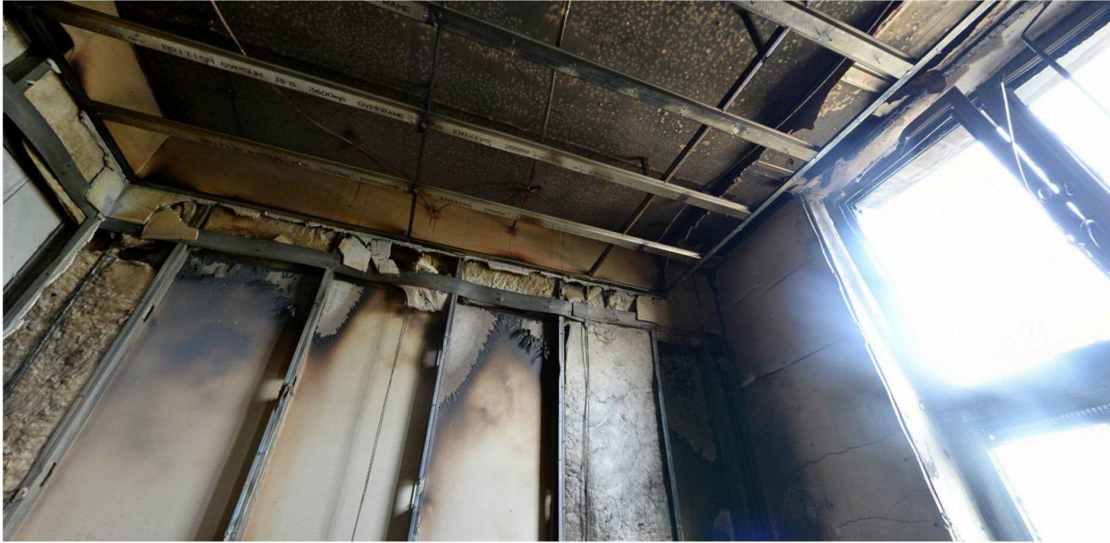
2212 5.2.3 INTERNAL PENETRATION SUMMARY

2213 In summary, the analysis of these images (and others around the building (Figures 10.48, 10.49 and 10.50 [4]))
2214 shows that penetration of the fire could have happened in multiple ways. While some components, like the
2215 fan, seem to be more vulnerable than others, there is no evidence that they would have represented a
2216 preferred path for an external fire to ignite the interior of a unit.

2217 Given the high levels of heat flux that would be incident on the external façade due to the external fire, a path
2218 for the fire to re-enter the building will inevitably be created. The controlling factor therefore for the
2219 subsequent damage in the interior of the building is the characteristics of the external fire not the
2220 characteristics of the window, or its components.

2221 5.3 FIRE AND SMOKE MIGRATION TO THE INTERIOR

2222 Once the external envelope of the building is breached by the external fire, the possibility of ignition of
2223 combustible materials within the units is introduced. These combustible materials will then lead to conditions
2224 which are controlled by the fire dynamics of a pre-flashover compartment fire [2,34] that could potentially
2225 lead to a post-flashover fire [35]. It is important to note that, despite major damage in many of the units, a
2226 significant number of flats only resulted in fires that did not attain flashover. This would have impacted on the
2227 temperature of the smoke and its capacity to ignite other combustible materials, although it is important to
2228 approach this issue with some caution. The presence of an external flame can result in a very hot and
2229 potentially thin ceiling layer. This ceiling layer might have a very high temperature, severely damaging the
2230 ceiling, but be too thin to be able to provide sufficient radiation to ignite materials close to the floor (these
2231 flames are commonly referred to as optically thin). It is therefore possible, in these very unique circumstances,
2232 to have very hot gases that can ignite materials when touching them but that will not lead to generalized
2233 burning or flashover. Figure 46 and Figure 47 show two examples of such cases. The damage in each case is
2234 different, more structural damage is evident in Figure 47, while more fire damage is evident in Figure 46, but
2235 neither case experienced flashover.

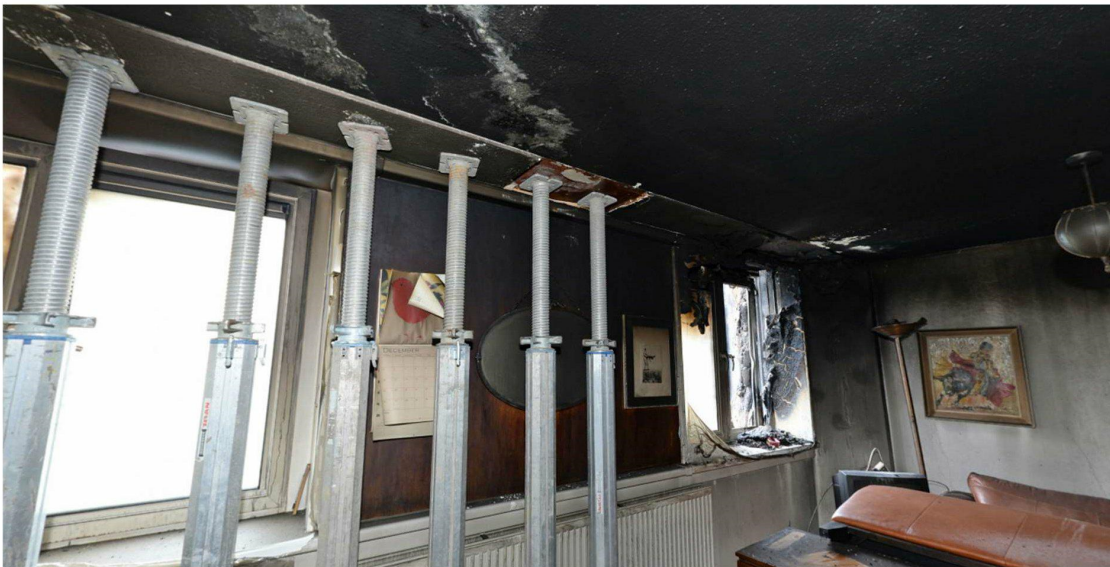


2236

2237 **FIGURE 46: FLAT 9 (LEVEL 3) WHERE THE FIRE IGNITED CEILING MATERIAL LEADING TO SPALLING, BUT FAILED TO ATTAIN**
 2238 **FLASHOVER**

2239 In other cases, the fires would have managed to ignite all the combustible materials within the compartment.
 2240 These will be discussed later in more detail because they are relevant to the breach of compartmentalization
 2241 of the units. Fires that did not attain flashover would have been less likely to thermally compromise the main
 2242 door of the unit given the distance between the windows and the main door.

2243



2244

2245 **FIGURE 47: FLAT 35 (LEVEL 6) CEILING SUSTAINED SEVERE DAMAGE, NECESSITATING STRUCTURAL SUPPORT WITHOUT REACHING**
 2246 **FLASHOVER CONDITIONS**

2247 5.3.1 EARLY PASSAGE OF SMOKE THROUGH THE BUILDING

2248 Once fires have entered the building, the next level of protection are the boundaries of the units. These
 2249 boundaries are fire resistant walls and doors. These fire-resistant walls and doors are intended to stop the
 2250 propagation of flames and smoke into the lobbies and stairs. The requirements for these doors are described
 2251 in Dr Lane's Phase One Expert report (Section 2.21 and Appendix I) [4]. These requirements pertain to fire
 2252 resistance, smoke seals and self-closing mechanisms. It is clear from the earlier stages of the fire at Grenfell
 2253 Tower that internal compartmentalization was breached and smoke had migrated into the stair lobby. Smoke
 2254 was observed from very early on emerging from windows in areas very far from where the external fire was
 2255 progressing (Figure 48 to Figure 52). This clearly indicates that the boundaries of at least two units had been
 2256 breached. These observations need to be further explored in Phase Two.



FIGURE 48: NIGHT VISION CAMERA (TIME: 2:00:12), SOUTH FAÇADE, SMOKE COMING FROM MID-LEVEL APARTMENT WINDOW



FIGURE 49: NIGHT VISION CAMERA (TIME: 2:01:30), WEST FAÇADE, SMOKE COMING FROM MULTIPLE WINDOWS ON LEVEL 20



FIGURE 50: NIGHT VISION CAMERA (TIME: 2:03:00), WEST FAÇADE, SMOKE COMING FROM MULTIPLE WINDOWS ON LEVEL 20 (FLAT 174)



FIGURE 51: NIGHT VISION CAMERA (TIME: 2:03:30), WEST FAÇADE, SMOKE COMING FROM MULTIPLE WINDOWS ON LEVEL 20 (FLAT 174 AND 175)



FIGURE 52: NIGHT VISION CAMERA (TIME: 2:14:57), WEST FAÇADE, SMOKE COMING FROM MIDLEVEL FLAT.

2257

2258 A review of past fire events in high-rise buildings involving internal smoke spread shows that in most cases
 2259 where casualties occurred, smoke had spread into vital parts of the building. Events with high casualties
 2260 include:

- 2261 • Andraus Fire, Sao Paulo, Brazil, 1972 – 16 fatalities, 375 injuries
 - 2262 ○ smoke entered stairwell
- 2263 • Joelma Fire, Sao Paolo, Brazil, 1974 – 179 fatalities, 300 injuries
 - 2264 ○ smoke entered stairwell
- 2265 • MGM Grand Hotel, Las Vegas, NV, 1980 – 85 fatalities, 600 injuries
 - 2266 ○ smoke travelled through the entire building because of unprotected openings in
 - 2267 compartmentalization walls
 - 2268 ○ Fans drew smoke from the mechanical room, spreading into occupied spaces
 - 2269 ○ Smoke spread in the elevator shaft due to doors remaining open on the first floor
- 2270 • Dupont Plaza, San Juan Puerto Rico, 1986 – 98 fatalities
 - 2271 ○ Smoke was coming through air conditioning system vents and was an initial warning
 - 2272 to the fire (alarms were not functioning). Smoke entered the foyer due to a missing
 - 2273 panel. Extensive compartmentalization breaching.

2274

2275 In contrast, events where compartmentalization was not breached and the stairwells remained clean of
 2276 smoke resulted in none or limited casualties:

2277

- 2278 ○ 7 buildings that experienced large external fires had no injuries or fatalities
- 2279 ○ 2 of the buildings had effective external compartmentalization that prevented the fire or
- 2280 smoke from spreading into the building until the occupants had all escaped
- 2281 ○ 2 of the buildings did have smoke spread/fire spread in the building. One of those buildings
- 2282 (Wooshin Golden Suites) had fire brigade access to the roof where many occupants were
- 2283 saved²⁴. Another building (Al Tayer tower) had an isolated staircase that held out smoke and
- 2284 fire until all of the occupants had left.

2285

²⁴ At the moment of writing this report there is no reliable information on how this was achieved, therefore, this matter needs to be further explored.

2286 The vital role of compartmentalization is expressed clearly in all Building Regulations and it is summarized in
2287 Dr Lane's Phase One expert report (Section 3, Section 4, Appendices I and J) [4]. At the point where the
2288 perimeter of the building is breached by the external fire, this becomes the next line of defence. It is therefore
2289 important to assess the performance of the compartmentalization to understand the role it played in allowing
2290 smoke migration through Grenfell Tower.

2291 5.3.2 COMPARTMENTALIZATION PERFORMANCE FOLLOWING FIRE RE-ENTRY

2292 Once the external fire has breached the boundary of a flat unit, the potential for ignition of items within the
2293 unit and a subsequent compartment fire is realised. At this stage, it is reasonable to assume that the
2294 compartmentalization separating this unit from the surrounding units and communal areas should be
2295 adequate to prevent the fire and smoke progressing in a way that compromises these areas.

2296 The performance of these boundaries is quantified by providing a regulatory specified, required level of fire
2297 resistance. Fire resistance refers to the ability of a building element to not exceed specified failure criteria
2298 (related to its function) for a duration of exposure to a specific thermal loading in a test furnace. The length of
2299 time that an element is required to perform in the testing environment is designated according to the expected
2300 fire load of the eventual occupancy in which the building element will be deployed. The fire load is a surrogate
2301 for the expected severity of the fire that could exist in that space, i.e. a larger fire load is expected to result in
2302 a more severe fire, a more severe fire requires a more robust building element, and therefore the building
2303 element is required to endure a greater time in the furnace test to be considered robust enough to perform
2304 adequately in the real fire.

2305 Figure 53 shows the temperature curve that a fire resistance test is required to follow. The insert shows two
2306 photographs of typical furnaces used to test elements that require fire resistance. Also indicated in the figure
2307 is a typical compartment fire temperature. As can be seen from the figure, a compartment fire temperature is
2308 very different to the temperature history followed by the regulatory test. Therefore, while fire resistance is
2309 presented in terms of time, it needs to be understood that fire resistance does not correlate to time to failure
2310 in a real event. All structural elements requiring fire resistance (i.e. doors, fire stop materials and other
2311 component parts of fire rated compartments), are required to be tested according to this specified testing
2312 regime.

2313 For the compartmentalization to be expected to perform in the case of a re-entrant fire, the severity of the
2314 compartment fire must be assumed to be primarily a result of the consumption of the fire load within the flat
2315 unit and the external fire's contribution assumed negligible. The external fire can then be simply categorised
2316 as the source of ignition of a pre-flashover fire. This is a reasonable assumption given that the amount of fuel
2317 provided by the cladding per unit area is less significant than the fuel within the flat and also because most of
2318 the energy from the external flames will be dissipated outwards.

2319

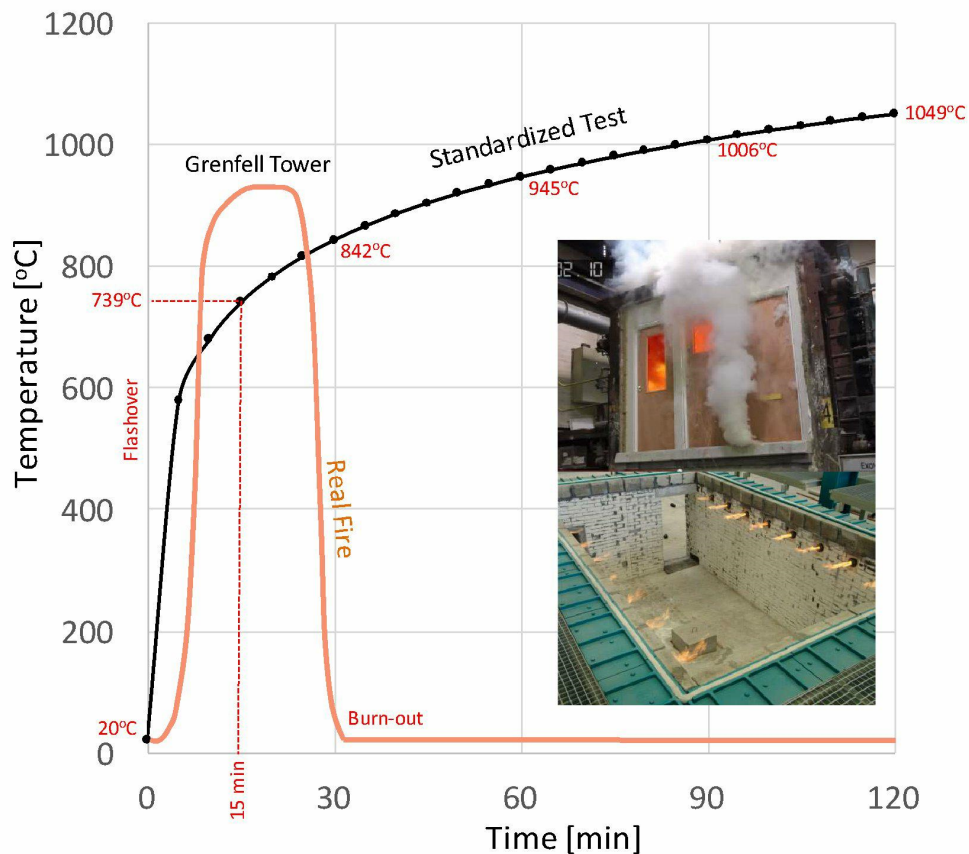
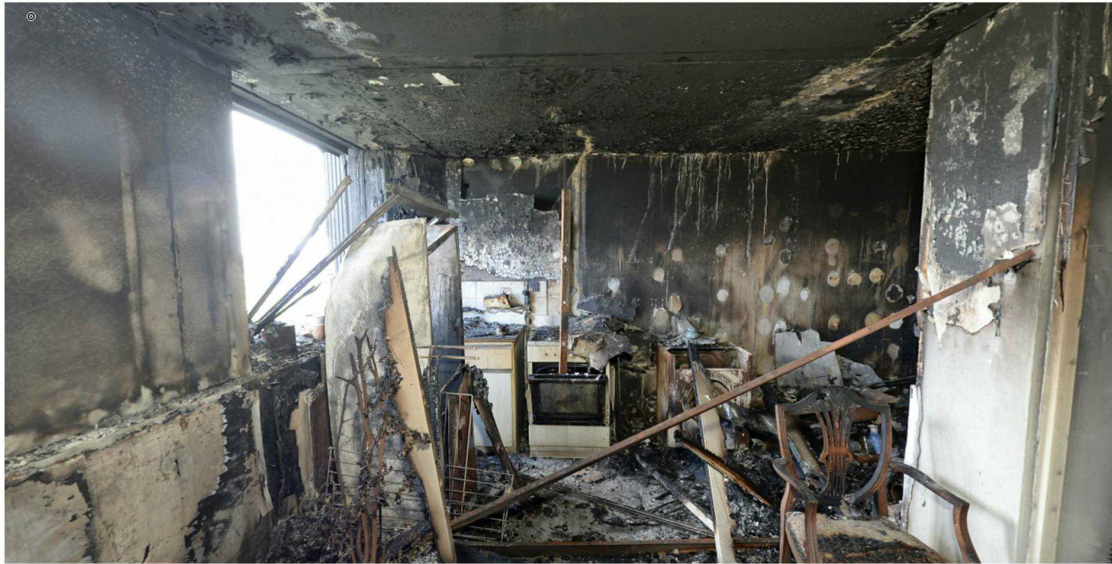


FIGURE 53: COMPARISON BETWEEN THE FIRE RESISTANCE TEST TEMPERATURE HISTORY AND THOSE OF A COMPARTMENT FIRE TYPICAL OF A RESIDENTIAL BUILDING COMPARTMENT. THE LABEL GRENFELL TOWER CORRESPONDS TO THE GREEN RANGE OF POSSIBLE VALUES. THE LABEL REAL FIRE IS AN EXAMPLE OF A POSSIBLE FIRE WITHIN THIS RANGE.

5.3.2.1 THE CONTRIBUTION OF THE RE-ENTRANT FIRE

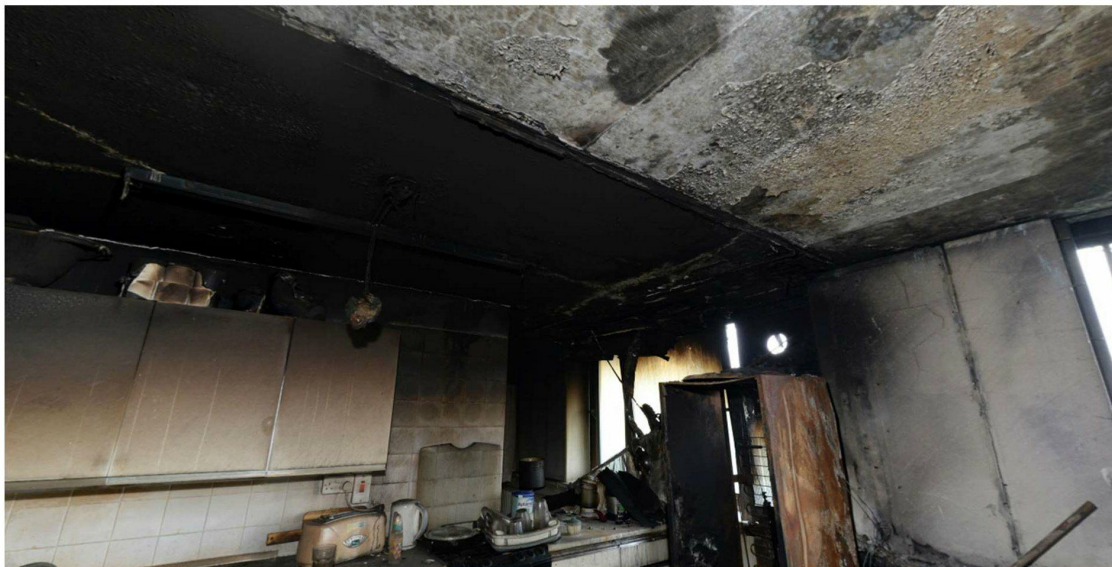
In the case of Grenfell Tower, a forensic quantitative assessment of the external fire contribution is not viable given the availability of evidence, however the external fire contribution can be assessed qualitatively by observation of the damage in flats where the external fire breached the compartmentalization.

It is important to note that, despite major damage in many of the units, a significant number of flats never attained flashover. This impacts on the potential temperatures of the smoke and its capacity to ignite other combustible materials, although it has to be interpreted with caution. As indicated earlier in this section, the presence of an external flame can result in a very hot and potentially thin ceiling layer creating the very unique circumstances of having a layer of very hot gases that could ignite materials when touching them but that will not lead to generalized flashover. Examples of this scenario can be seen in Figure 54 and Figure 55.



2334

2335 **FIGURE 54: FLAT 63 (LEVEL 9) SHOWING SEVERELY DAMAGED CEILING IN ROOM THAT DID NOT REACH FLASHOVER. NOTE**
2336 **UPHOLSTERED CHAIR IN LOWER RIGHT**



2337

2338 **FIGURE 55: FLAT 54 (LEVEL 8) SHOWS SEVERELY DAMAGED CEILING IN KITCHEN, HOWEVER FLASHOVER HAS NOT OCCURRED**

2339 An assessment of the damage in flats other than that of the fire origin (Flat 16) is described later in detail in
2340 Section 6.2. Of the 113 flats where fire or smoke breached the compartmentalization, 13 experienced minor
2341 damage, 9 experienced moderate damage, and 91 experienced major damage.

2342 Minor damage is defined as smoke ingress, low levels of heat damage, or small localised fires around the point
2343 of entry. This may be in the form of soot deposition, localised deformation of polymer-based furniture and
2344 fittings, or evidence of localised burning. Figure 56 and Figure 57 shows typical examples of this level of
2345 damage. This is not expected to challenge the compartmentalization of the flat unit.

Moderate damage corresponds to localised damage around the point of re-entry of the fire where this has occurred in more than one location within a single flat unit. This could range from localised charred surfaces to localised fires that failed to involve other objects in the room and thus did not progress to flashover. Figure 58 and Figure 59 show typical examples of this level of damage. In certain cases, the localised fires resulted in some level of damage to components such as windows or furniture but no structural damage could be observed.

Severe damage is characterized by the presence of spalling on ceilings and compartment walls, as well as evidence of structural damage to ceilings and compartment walls. In some cases, one room may have significant structural damage (e.g. living room), while the remainder of rooms had no visible structural damage with spalling on ceilings and walls present and sometimes not present. Examples of this degree of damage are displayed in Figure 60 and Figure 61. The impact of these fires on compartmentalization is difficult to assess, nevertheless it is expected that damage to the walls and doors separating the unit from the lobby would have been minor. This is mostly because of the distance between the perimeter of the building and the boundary to the lobby.

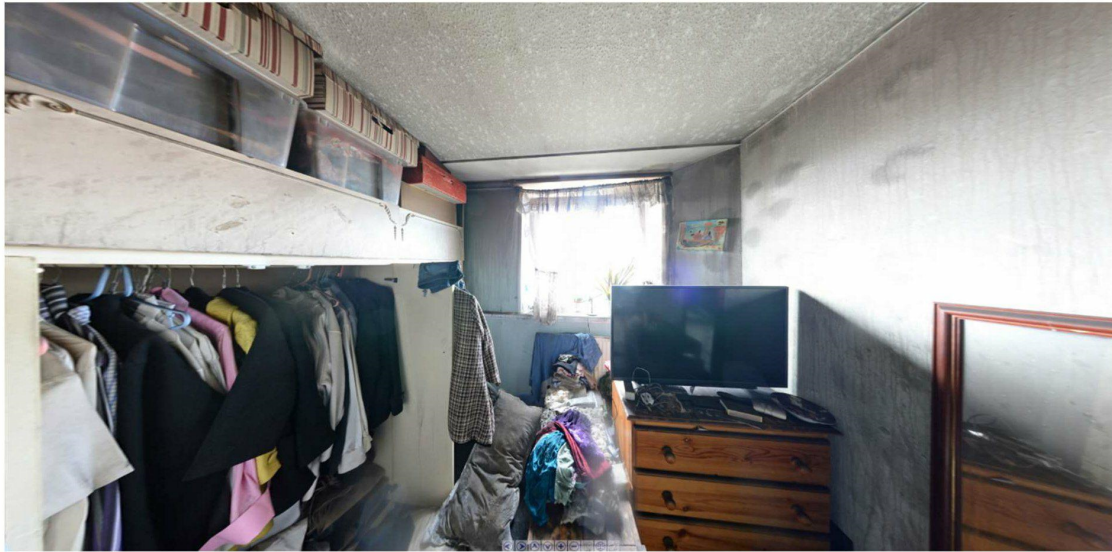
Major damage is typified by an ignition resulting from external flaming that subsequently develops into a fully-developed compartment fire (flashover). The majority of the sources of fuel within the room or even flat would be involved in the fire and without intervention, consumed by it. This level of fire is expected to challenge the compartmentalization. Examples of this type of damage are shown in Figure 62 and Figure 63.

The presence of this entire range of behaviours indicates that the influence of the external fire alone is not sufficient to consistently result in a fully-developed fire in a flat unit. This implies that the heat introduced by the external fire is typically only significant locally to the entry point, and it is the characteristics of the fuel distribution in a flat and specifically of the first internally ignited item(s) that determines if a fire will subsequently grow to be fully-developed. The aleatory (i.e. unpredictable) distribution of combustible materials in residential units correlates well with the variability of damage in different units. It is very likely that in a residential unit there will be sufficient fuel to attain flashover and develop a fire that could lead to major damage, thus is not surprising that 91 of the 113 affected flats experienced major damage.

It should therefore be considered that, with regard to the compartmentalization of the internal boundary of a flat unit, the thermal loading imposed by the external fire is secondary in comparison with the thermal loading imposed by combustion of the furniture and fittings. Given the type of construction of Grenfell Tower and the minor compartmentalization non-compliances between flats (Section 4 [4]) it is also appropriate to assume that the compartmentalization separating each flat from neighbouring flats should be capable of restricting any significant passage of smoke, heat and fire from one unit to another.

Finally, it is expected that for the 91 units with major damage, compartmentalization of the boundary between the unit and the lobby (in particular the doors) would have been challenged.

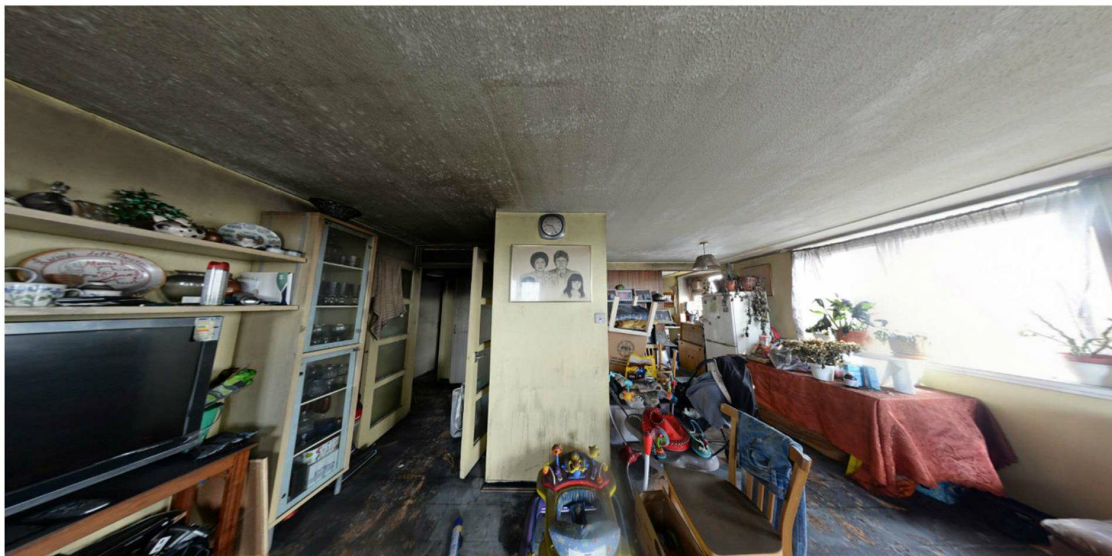
2380



2381

2382 **FIGURE 56: EXAMPLE OF MINOR DAMAGE FROM FLAT 62, FLOOR 9.**

2383



2384

2385 **FIGURE 57: EXAMPLES OF MINOR DAMAGE FROM FLAT 62, FLOOR 9.**

2386

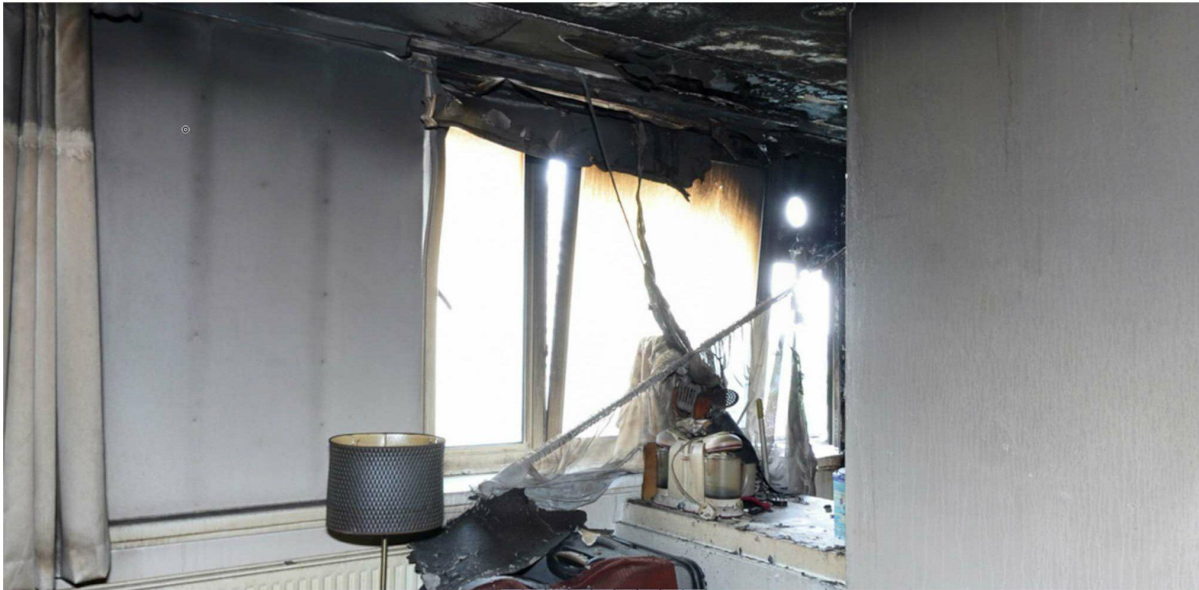


FIGURE 58: EXAMPLES OF MODERATE DAMAGE FROM FLAT 93, FLOOR 12.

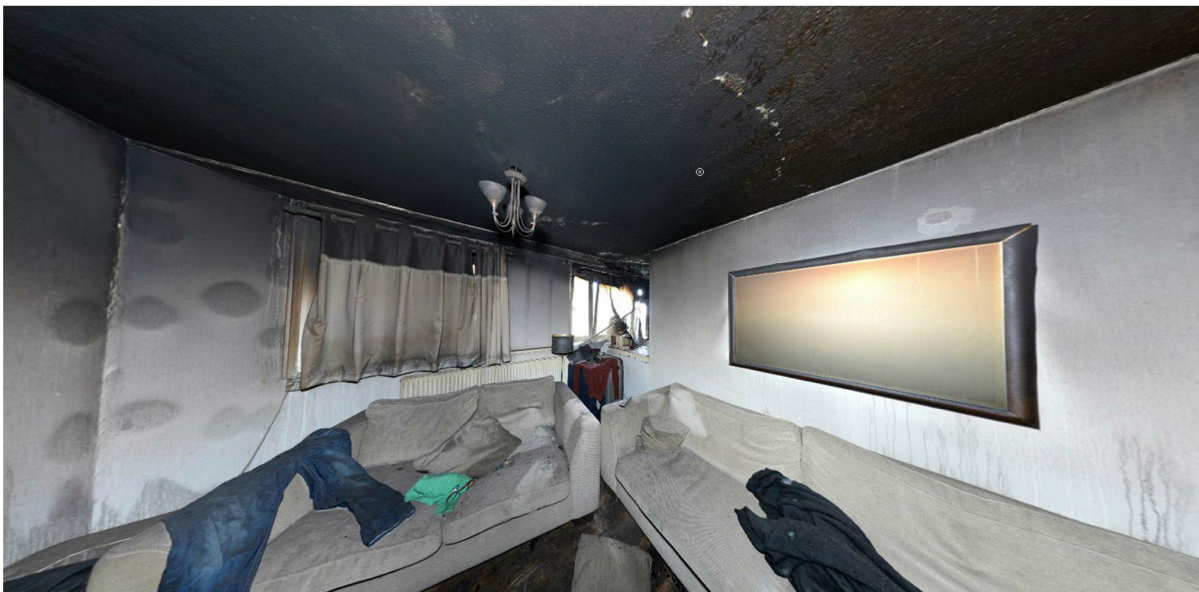
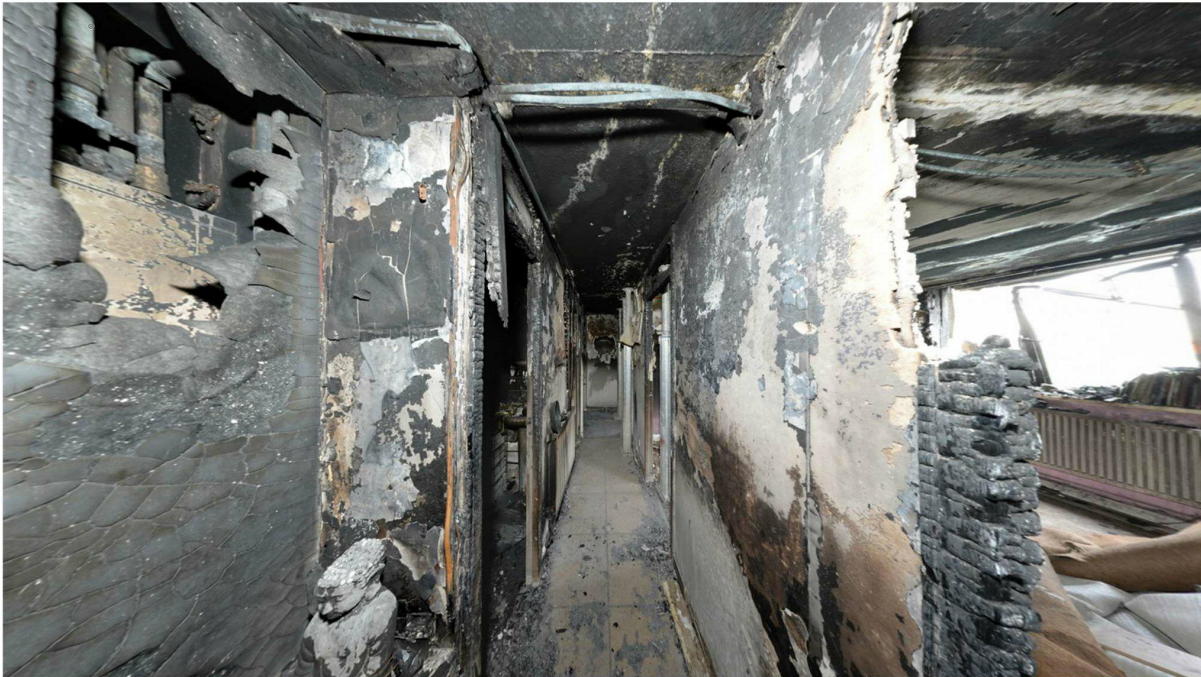


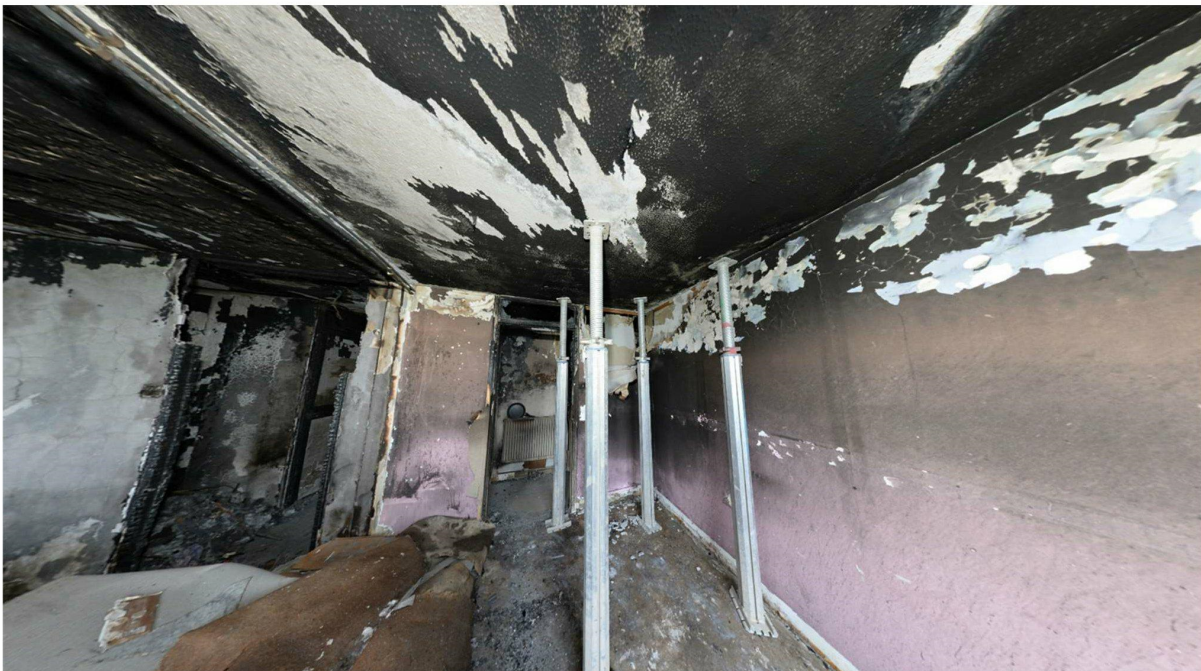
FIGURE 59: EXAMPLES OF MODERATE DAMAGE FROM FLAT 93, FLOOR 12.



2393

2394 **FIGURE 60: EXAMPLES OF SEVERE DAMAGE FROM FLAT 45, FLOOR 7.**

2395



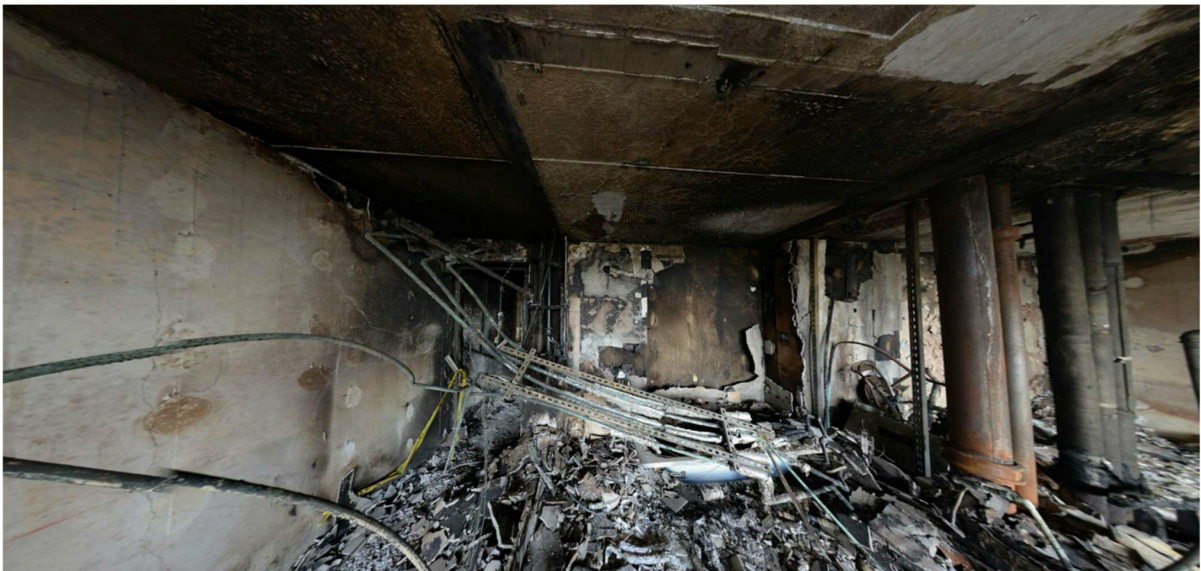
2396

2397 **FIGURE 61: EXAMPLES OF SEVERE DAMAGE FROM FLAT 45, FLOOR 7.**

2398



2399

2400 **FIGURE 62: EXAMPLES OF SEVERE DAMAGE FROM FLAT 114, FLOOR 14.**

2401

2402 **FIGURE 63: EXAMPLES OF SEVERE DAMAGE FROM FLAT 114, FLOOR 14.**2403 **5.3.2.2 FAILURE OF FLAT DOORS**

2404 Following the fire at Grenfell Tower, investigations have noted a number of flat doors that were damaged to
2405 various extents. Such damage to compartmentalization therefore represents a viable path for fire and smoke
2406 migration to the communal lobbies, egress stair, and surrounding flats. It is important therefore to establish
2407 under what conditions these doors might have failed and to ascertain how this relates to the timeline of the
2408 fire and smoke progression through Grenfell Tower, thus contextualising the impact of any door failure.

Tests conducted at BRE on flat doors [36] removed from the building demonstrated a fire resistance rating of the order of 15 minutes. As described previously in this section, this means that the doors failed defined performance criteria after 15 minutes of thermal exposure to the ISO 834 temperature-time curve (Figure 53) within a furnace. This corresponds to a failure temperature of the order of 740°C (739°C in Figure 53). Figure 53 also shows the evolution of the temperature in a typical residential compartment. In a fire that starts within the compartment, flashover will most likely occur in the first 5 minutes when temperatures reach values between 500°C and 600°C, the post-flashover fire can then reach temperatures as high as 1200°C. Eventually, all combustibles will be consumed and burn-out will occur. This will generally take no more than 40 minutes. If the fire is ignited externally, flashover can be attained very rapidly but the characteristic compartment temperatures will remain the same because a post-flashover fire is not limited by the fuel but by the available ventilation.

To establish the typical range of post-flashover compartment fire temperatures, a brief analysis is performed for a typical one-bedroom flat in Grenfell Tower. Upper and lower bound temperatures and corresponding fire durations are established for both of the principle rooms in this flat configuration.

Temperatures are assessed using the experimental data provided by Thomas [37] (Figure 64) which uses an inverse opening factor, ϕ' , to establish a representative compartment temperature. The inverse opening factor represents the relationship between the size of the compartment and the size of the ventilation, assuming that the amount of combustion in a post-flashover fire is limited by the air available to it. Inverse opening factors for these spaces range from approx. 10 – 25 $\text{m}^{-1/2}$. This corresponds to characteristic compartment temperatures in the range of 850 – 1000°C.

To estimate the duration of burning for such a compartment, the experimental data provided by Kawagoe [38] (Figure 65) is used to determine characteristic burning rates, as a function of the typical fuel type and compartment temperature. Assuming a mixture of wood and PU foam as the principle fuel sources in a bedroom or living room, this gives burning rates in the range 0.012 – 0.018 $\text{kg/m}^2\text{s}$.

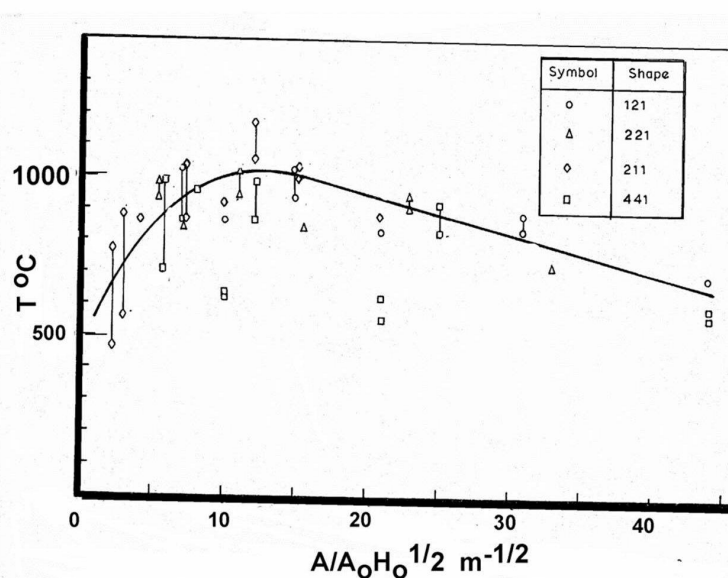
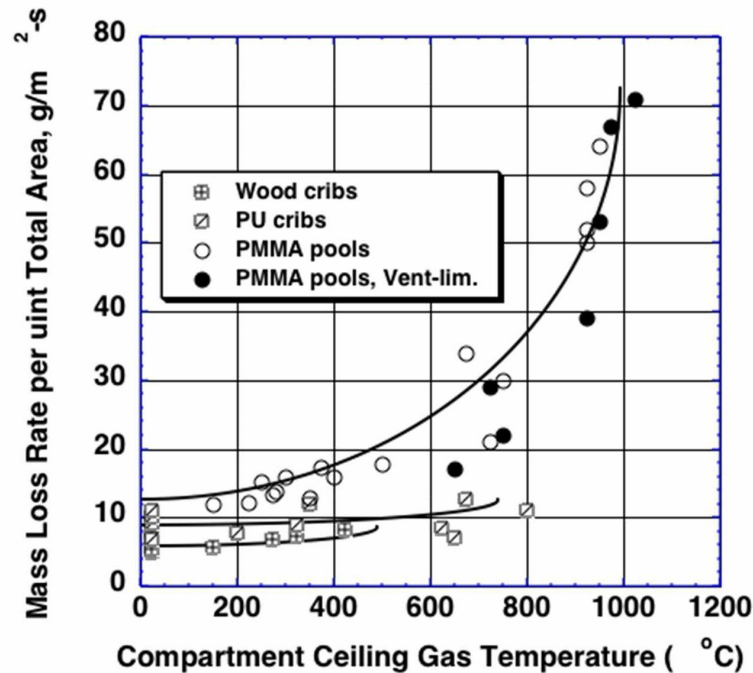


FIGURE 64: THE PLOT BY THOMAS [37] PROVIDES AN INDICATION OF THE TEMPERATURE OF A FULLY-DEVELOPED COMPARTMENT FIRE BASED ON THE INVERSE OPENING FACTOR.

2436



2437

2438 **FIGURE 65: THE PLOT BY KAWAGOE [38] DEFINES BURNING RATE [G/M².S] AS A FUNCTION OF COMPARTMENT TEMPERATURE**
 2439 **[°C].**

2440 Eurocode 1 [39] gives an average fire load density for a dwelling of 780 MJ/m². For the assumed fuel sources,
 2441 the typical energy content is taken as ~30 MJ/kg [40], which equates to a fuel load of approximately 26 kg/m².
 2442 Given the estimated range of burning rates from Figure 65, this gives a fire duration of the order of 25 – 35
 2443 minutes for a single compartment.

2444 It has been reported [35] that standard testing of the doors showed failure at approximately 15 min.
 2445 Furthermore, it is reported that, given the composition of the doors (i.e. Section 14.5.12, Appendix I [4]),
 2446 failure was characterized by flaming of the doors. If the failure times of these tests are used to indicate the
 2447 conditions necessary for failure, then Figure 53 shows that the gas temperature during the test when failure
 2448 occurred was of the order of 740°C. This temperature is above characteristic flashover temperatures and
 2449 therefore would most likely occur in cases where the units had major damage. Furthermore, failure of the doors
 2450 would have only occurred after conditions in the unit were untenable. Section 4.4 indicates that the vertically
 2451 propagating fire was observed to start internal fires on the 5th, 12th and 22nd floors as early as approximately
 2452 01:18, 01:24, and 01:28 respectively. Therefore, the lobbies in these floors could have been compromised
 2453 prior to 02:00.

2454 In cases where moderate or severe damage was observed, smoke and flame entering the unit from external
 2455 fires would not provide sufficient thermal insult for sufficient duration to affect such failures. This is evidenced
 2456 by the fact that the flat doors in flats where damage was of this nature (See Section 5.3.2.2) i.e. no post-
 2457 flashover fire, did not experience damage that cannot be explained by either firefighter intervention or
 2458 thermal insult from the communal lobby side due to failure of all other flat doors on that floor. In the majority

2459 of cases where flat doors were damaged (and still identifiable), this coincided with a major, post-flashover fire
2460 in the flat.

2461 5.3.2.3 MECHANISMS FOR INTERNAL SMOKE SPREAD

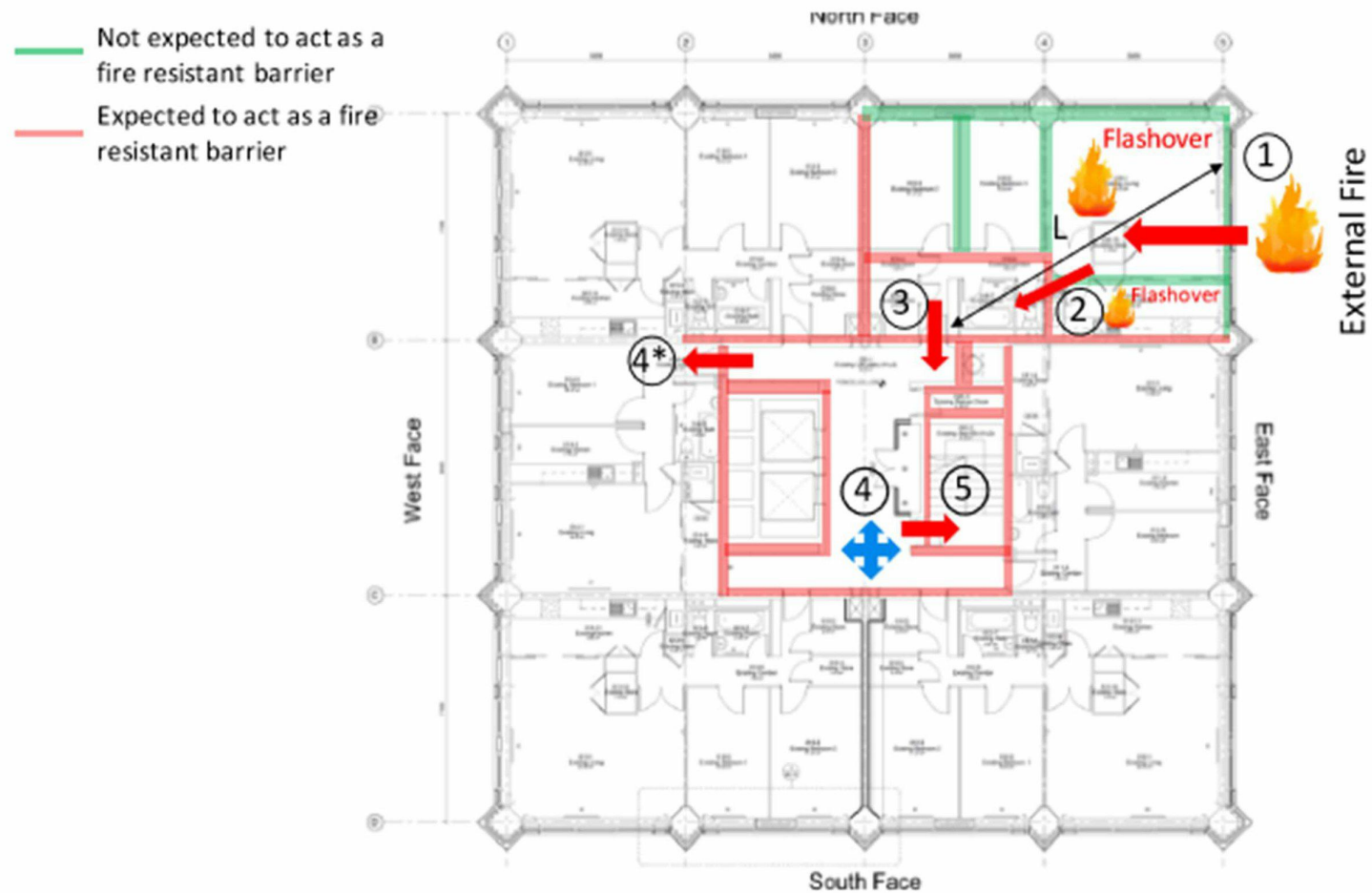
2462 As explained above, for a fire to bring smoke and heat to the stairs it is necessary to breach several barriers.
2463 For the purposes of this section, a barrier is defined simply as a physical obstruction to the smoke and heat.
2464 Some of these barriers have regulatory requirements for levels of fire resistance, however for the purpose of
2465 this section, barriers are differentiated by an expectation of their level of robustness. These are illustrated in
2466 Figure 66.

2467 Green lines indicate barriers that are not expected to afford significant robustness in respect to the resistance
2468 to the passage of heat and smoke, while pink lines represent barriers that are expected to provide a significant
2469 level of robustness. Red arrows indicate a barrier of either type that must be breached for smoke and / or heat
2470 to reach the protected stairwell. Barrier (1) is the building façade. As explained in previous sections, there are
2471 no expectations for windows on the external wall to protect the building in a manner that they will serve as a
2472 barrier to an external fire. Nevertheless, this will be deemed the first level of containment. Barrier (2) is defined
2473 as the boundary of the internal hallway within the unit (walls and doors). This hallway is defined as a protected
2474 hallway therefore, these elements are expected to represent a robust barrier. Barrier (3) is the entrance door
2475 to the unit. Again, this is expected to provide a robust barrier. Barrier (4) is defined as the lobby ventilation
2476 system which, while not a physical barrier, is expected to provide a preferential pathway for smoke in the
2477 lobby. Finally, barrier (5) is the stair door which is expected to provide a robust barrier to smoke and heat
2478 ingress into the stair.

2479 If the breach of barrier (1) was not sufficient to ignite the combustible materials in the compartment adjacent
2480 to the external wall, then smoke from the external fire would have had to migrate through the internal doors
2481 (2), the unit entrance door (3) overwhelmed the lobby ventilation system (4) and then finally the stair door
2482 (5). The fire itself would have been too remote to thermally damage any of these layers as distance L (the
2483 distance between the point of entry of the flames and subsequent barriers) is too large. Smoke migration could
2484 have been either through poor design of walls and doors or poor installation or maintenance leading to
2485 leakages.

2486 Another alternative is if all the doors were left open. The state of the lobby ventilation system, the doors and
2487 the walls are described in detail in Dr Lane's Phase One expert report [4]. It was established that no significant
2488 issues could be found with the walls (Section 19.7.8 [4]) but that there was no sufficient evidence to establish
2489 the state of the lobby ventilation system (Section 19.7.21 [4]). So, smoke migration had to occur through the
2490 doors.

2491 Barrier (4*) represents doors to other units that open to the lobby. Section 5.3.1 of this report shows that path
2492 (4*) occurred in several places slightly after 02:00 further emphasizing that smoke migration had to occur
2493 through the doors. The issue of self-closing mechanisms for the flat and stair doors thus needs to be
2494 considered.



2495

2496

Figure 66: Mechanisms of smoke spread to the lobby, assuming fire has spread inside via the external wall assembly

2497 If the breach of containment was sufficient to ignite combustible materials in the compartments adjacent to
 2498 the external wall, then flames and smoke, hot enough to cause damage to the flat doors, would have been
 2499 present. The fire would have been brought towards the entry of the unit, thus, distance L will be small enough
 2500 that the unit doors (2) and entrance door (3) would have been damaged and, given their characteristics, would
 2501 have ignited. There is sufficient evidence to establish that the doors ignited in many of the units with major
 2502 damage. Ignition of the doors would have posed a severe challenge to the lobby. Because of its small size, the
 2503 lobby would have rapidly filled with smoke but also potentially with flames. Post fire inspections by Dr Lane
 2504 indicate that there is sufficient evidence of high temperatures between floors 13 and 16 (Section 19.6.7 [4]).
 2505 The lobby ventilation system (4) would have been inevitably overwhelmed and stair doors (5) and other unit
 2506 doors (4*) would have also been compromised. For this scenario, there is no need for the doors to be open
 2507 for smoke to migrate into the stairs.

2508 The following sections discuss in more detailed how all these levels of containment could have potentially
 2509 been breached.

2510 5.3.2.3.1 OCCUPANT EGRESS

2511 Occupant egress necessitates the opening of fire doors; thus smoke would have been able to escape into
 2512 communal lobbies during occupant movement/evacuation and, to a lesser extent, into the egress stair. CCTV
 2513 video evidence from the Level 7 lift lobby corroborates this breach of compartmentalization
 2514 [MetUSB:NORTHLEIGH/Op Northleigh Spread of Fire/Interactive/CCTV/7th floor.mp4]. This action is a very
 2515 brief event and the impact of this action is likely to be negligible providing doors are closed promptly behind
 2516 the evacuating occupants.

2517 5.3.2.3.2 FIRE DOOR DEFICIENCY/LACK OF DOOR CLOSERS

2518 It has not been possible to establish if apartment doors were not fitted with functioning door closers and or
 2519 installed deficiently [Section 2.15.15 [4]] nor is there conclusive evidence that door closers on the stair fire
 2520 doors were not working (Section 2.21.34 [4]). Nevertheless, if any of these mechanisms did not function during
 2521 internal circulation and evacuation, smoke would have been able to spread from fire affected compartments
 2522 into communal lobbies. This is a viable mechanism for the early passage of large quantities of smoke through
 2523 the building (Section 5.3.1) and for the early compromise of lift lobbies in and around floors where
 2524 compartment fires were ignited within Stage 2 (Section 4.4).

2525 5.3.2.3.3 FIREFIGHTER INTERVENTION

2526 Emergency response by firefighters frequently has an impact on compartmentalization. Typically, this is not
 2527 an issue as occupants that are able to will have already evacuated. In the case of a “stay put” strategy most
 2528 occupants will remain safe in their units. This leaves firefighters free to fight the fire and perform any required
 2529 search and rescue activities. Firefighters have specific protocols with regards to high rise buildings, however
 2530 as outlined in Mr. Todd’s Phase One expert report [1] and as is likely to be outlined in their operational
 2531 procedures (information remains incomplete at the moment of writing this report), these protocols will be
 2532 driven by the unique characteristics of these buildings and, by extension, the implications for firefighter safety
 2533 that these characteristics bring about.

2534 One characteristic is that fire appliances and hoses cannot always directly reach the compartment of fire origin
2535 therefore requiring responders to enter the building and connect hoses to risers. Typically, this action is
2536 performed at a bridgehead set up two floors below the floor of the fire compartment to allow responders to
2537 enter the floor on which the fire is located and be primed to immediately fight the fire, should it be necessary.
2538 This tactic of establishing a bridgehead beneath the fire floor necessitates running hoses via an emergency
2539 stair, and in doing so propping open the door to the stairwell and flat simultaneously. This will potentially
2540 result in the passage of smoke into the egress stair which will reduce the capacity of the stair itself due to the
2541 presence of the hose.

2542 In the context of a single unit fire and a functioning “stay put” strategy, this practice is acceptable as occupant
2543 use of the stair is minimal and restrictions caused by the presence of the hose and smoke in the stair are
2544 therefore negligible. This is borne out by reports from the period of time following the initial firefighting
2545 activity in Flat 16. The fire was at a pre-flashover stage when the hoses were potentially compromising the
2546 egress stair, thus smoke production and migration into the egress stair was minimal. There is a continued,
2547 steady flow of occupants down the stair subsequent to these actions ([Section 14 [4]] and Section 5.3.4). Once
2548 the scenario escalated however, firefighting activities became required on multiple floors and smoke from
2549 increasingly developed fires was able, by some means, to reach the stairwell which also later became
2550 increasingly unnavigable due to the quantity of hoses present. These issues are discussed in great detail in Dr
2551 Lane’s Phase One expert report (Sections 14, 17 and 19) [4] and will therefore not be further discussed here.

2552 Beyond the logistics of supplying water, gaining access to flats as part of firefighting and search and rescue
2553 activities may require forced entry. This has the potential to compromise the integrity of the door and, by
2554 extension, its ability to fulfil its role as a fire barrier. Again, in the context of a single flat fire which is controlled
2555 and extinguished by the responders, this is not a significant issue. Once multiple fires exist however, the effect
2556 of the loss of fire barriers on the single egress stair is compounded. Firefighter testimony establishes numerous
2557 occurrences of damage to flat entry fire doors by responders during both firefighting and search and rescue
2558 activities [MET00005251, MET00005700, MET000080558, MET00005429, MET00005467, MET00005413].

2559 Statements of the initial responders [MET00005251] establishes that firefighters forced the door of Flat 16 as
2560 they initially responded to the kitchen fire. Even though the initial kitchen fire was extinguished, a later more
2561 severe fire event occurred within the flat, following re-entry of the fire into a bedroom.

2562 [MET00005700, MET000080558] reports response to a fire that developed in Flat 26 on Level 5, immediately
2563 above Flat 16, following re-entry of the fire from the cladding. In this case the firefighters “kicked the door in”.
2564 Unable to extinguish the fire due to the hose being snagged elsewhere, the firefighters retreated to the lobby
2565 where they noted that conditions in the lobby were “almost as bad as in the flat”. In this case, a flashover
2566 event occurred later in time potentially without the benefit of a fully functioning fire door at the flat entrance
2567 to protect the lobby.

2568 Seemingly later in the fire, at an undetermined time, [MET00005429] describes firefighting activities on the
2569 12th floor where numerous fire doors were forced open. “...we think entered the twelfth floor [sic]. The door
2570 was opened by WM McKay and I pulsed some water into the floor. We then moved into the floor and started
2571 fire-fighting. First, I fired water into the flat down the left hand end which knocked the remainder of the door
2572 off its hinges and created a lot of helpful light and cooler air. We then tried to get into the flat next to it. Fired
2573 the jet into the flat after forcing our way in as there was bedding behind the door. After more water was fired
2574 into the flat we then searched it and found nothing. Moved onto the next flat, number 82. Same scenario with
2575 bedding behind the door. ”

2576 [MET00005467] reports using an enforcer to smash through a door panel, “cow kicking”, and “smashing” doors
 2577 open in order to search 4th and 5th floor flats. Re-entering the building later to resume search and rescue
 2578 activities on the 11th floor, the same statement describes taking sledgehammers and axes, presumably to gain
 2579 access to individual flats. [MET00005413] describes braking a hole in the door (9th floor) beneath the door
 2580 handle in order to reach through to open it.

2581 These tactics, though likely inconsequential under a controlled “stay put” strategy, have a strong impact on
 2582 the protection of egress paths and thus may disable any strategy change, later in time, when occupant
 2583 evacuation becomes more critical.

2584 Further investigation is required to understand if continued following of the “stay put” protocol and
 2585 corresponding firefighting, search and rescue activities, contributed to the rapid decline of general tenability
 2586 in the egress passages. It is important to understand what the implications were for the egress routes given
 2587 how early on in the incident the framework for a “stay put” strategy was undermined This need is highlighted
 2588 further when considering other fires of a similar nature, described in Section 4.2, where maintained tenability
 2589 of the egress stair was key to ensuring the safe evacuation of building occupants once extensive external fire
 2590 spread had occurred. This matter will require significant attention in Phase Two.

2591 5.3.2.3.4 LARGE SCALE EFFECTS

2592 For completeness, other mechanisms of smoke migration have been evaluated. Large-scale buoyancy (stack
 2593 effect) and lift shafts provide mechanisms for vertical smoke movement. Two mechanisms, described briefly
 2594 here, are associated with such vertical smoke movement.

2595 **Stack Effect:**

2596 The stack effect is the process through which air flows through a building due to temperature differential
 2597 between the inside and outside of the building. When the outside air is below room temperature, this cold air
 2598 enters the building and heats up to room temperature and flows upwards. At Grenfell Tower on the day / night
 2599 of the fire, outdoor temperatures ranged from around 18.3°C (12:00 PM)-15.5°C (5:00 AM), or slightly below
 2600 room temperature. Some qualitative conclusions can be drawn from this:

- 2601 • The stack effect will be fairly negligible in driving smoke up the building.
- 2602 • The stack effect may draw smoke into the elevator shaft, which could potentially rise up under its own
- 2603 buoyancy.

2604 It is also possible that, later in the fire, this effect may begin to happen in reverse due to the outside air being
 2605 heated by an exterior fire as well as many windows being breached. This effect could have led to significant
 2606 motion of smoke around the building. Currently research into this scenario is limited and therefore the stack
 2607 effects on Grenfell Tower are difficult to assess.

2608 While the influence of the stack effect might be relevant, its effects would have been very unique to the
 2609 Grenfell Tower fire scenario. It is not clear if any lessons might be learnt from a detailed analysis of the stack
 2610 effect, thus I consider studying this phenomenon of lesser priority.

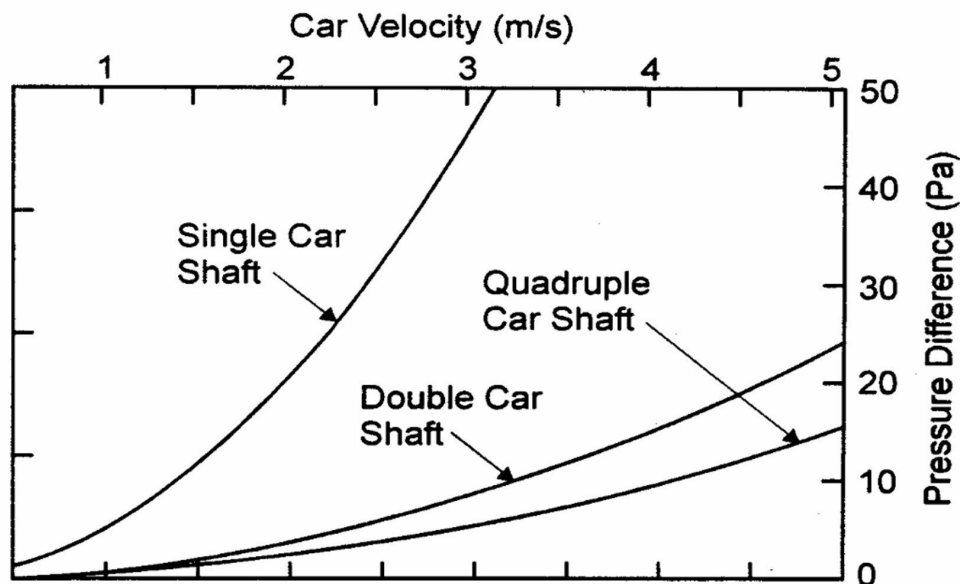
2611

2612

2613 **Piston effect in lift lobby:**

2614 The piston effect is the process where a vertically-moving lift creates suction pressure in its wake, which pulls
 2615 air from in front of it to the area behind it. This mass flow can then pull air through the openings and leakage
 2616 areas between the elevator shaft and the wall, creating a vertical flow between floors above an elevator and
 2617 below an elevator.

2618 The number of necessary assumptions regarding the air flow and exact conditions of the building preclude the
 2619 undertaking of a detailed analysis of the impact of this effect. However, the NFPA reference "Smoke
 2620 Movement and Control in High Rise Buildings" chapter 4.5 [42] provides a comprehensive background to this
 2621 issue. In a multiple-car elevator shaft, the adverse effects of a single elevator moving are typically negligible.
 2622 From video evidence [MetUSB:NORTHLEIGH/Op Northleigh Spread of Fire/Interactive/CCTV/Southlift.mp4] of
 2623 the south lift it can be inferred that this lift remained at the 2nd floor between approximately 01:03 and 01:37,
 2624 thus it can be assumed that these early stages of a fire can be treated as a single car in a double car shaft. The
 2625 chart Figure 67 shows the upper limit pressure difference between the elevator shaft and the lobby and it has
 2626 been calculated that the elevator car in Grenfell Tower moved at between approximately 1.5 m/s. Thus, the
 2627 max pressure difference is around 3 Pa, which is negligible. This effect can therefore be discounted and should
 2628 be given no further attention.



2629
 2630 **FIGURE 67: PRESSURE DIFFERENCES AS A FUNCTION OF CAR VELOCITY FOR LIFT SHAFTS.**

2631 5.3.2.3.5 MISSING OR DAMAGED FIRE STOPPING

2632 The state of the fire barriers leading to the lobby (Section 19.7.8 [4]) and in particular the stair enclosure shows
 2633 only minor weaknesses in regard to its capacity to deliver adequate compartmentalization (Section 19.6.2 [4]).
 2634 These often provide small leakage paths for smoke to pass, nevertheless do not seem to have had a major
 2635 impact on what should be smoke proof compartmentalization.

2636 5.3.2.3.6 VIA THE SMOKE CONTROL SYSTEM

2637 It is unclear if the smoke management system, designed to vent smoke from communal lobbies, performed as
 2638 specified or was indeed even compliant (Section 19.7.21 [4]). A correctly designed and specified system would
 2639 be sized to perform within the framework of a contained single compartment fire, with the intention of
 2640 maintaining a single lobby as passable. Given the scale of the event and the number of lobbies that were
 2641 simultaneously compromised by smoke ingress, a fully functioning, compliant system would have provided
 2642 negligible benefits to egressing occupants, thus any discussion of its compliance or functionality is secondary
 2643 in the context of the Grenfell Tower fire.

2644 5.3.3 INTERNAL SMOKE SPREAD

2645 The following section provides an approximate overview of the spread of fire and smoke, from the exterior
 2646 façade, via individual flats, to the interior common elements of the tower. An approximate timeline is
 2647 constructed from 999 calls, firefighter statements and videos and images to reconstruct as accurately as
 2648 possible the time period until general conditions within the building could be deemed as untenable.

2649 The previous sections have analysed the potential for smoke migration on the basis of physical variables and
 2650 fire dynamics. This section takes information from the event with the purpose of contrasting this information
 2651 with the physical arguments made in previous sections. This analysis is not intended to be comprehensive, but
 2652 is presented to demonstrate the importance of contrasting different forms of information. Dr Lane's Phase
 2653 One expert report [4] provides a complementary, and in many cases more detailed analysis of this information.
 2654 Correlation of all this information, and any new information made available, should be conducted as part of
 2655 Phase Two.

2656 Despite the many photos and videos available for review, limited time-stamped photographs and videos exist
 2657 from which to build an internal smoke spread timeline. Exterior photographs taken during the fire event were
 2658 analysed to help infer smoke/fire spread within compartments, however, the quality of available images
 2659 limited the effectiveness of this approach.

2660 The most reliable videos from of the interior of the building during the event were CCTV footage provided by
 2661 the Metropolitan Police. These CCTV cameras were located at:

- 2662 • Inside the South Lift
- 2663 • Ground floor Lift Lobby
- 2664 • Level 7 Lift Lobby

2665 Furthermore, the following sources were used to provide temporal information:

- 2666 • Transcripts of 999 calls handled by the LFB and other fire authorities.
- 2667 • CCTV exit times (MET000080493)
- 2668 • Facebook Live video from Rania Ibrahim

2669 The data recorded in Table 5 is used to establish a smoke movement timeline for the first hour of the fire
 2670 (00:54 to 02:00). When residents from the same apartment make multiple calls, additional calls are listed
 2671 under the time of the first call. While this list is not complete, it is indicative of rates of internal smoke spread.

2672

| Time | Action | Evidence |
|-------|--|---|
| 00:54 | LFB 999 call: Resident of Flat 16 (Level 4) indicates fire in the flat kitchen: Caller reports a fire in Flat 16 on the 4 th floor. Refers to the “fridge”. Caller is outside and says “...quick, quick, quick ... It’s burning”. | LFB00000301 |
| 00:56 | Four people enter the south lift. Lift rises to Level 4, doors open and smoke spills into lift from lift lobby. | NORTHLEIGH/Op Northleigh Spread of Fire/Interactive/CCTV/Southlift.mp4 |
| | One of the lift occupants, Miguel Alves: “I just arrived when the fire started...I was in the lift, I pressed 13, and somebody pressed four.” When the doors opened at the fourth floor, where the fire had started, smoke billowed into the lift, Miguel said. “I just came out of the lift because I didn’t know what was going on, and I went up by the staircase to wake up my son and daughter.” | https://www.theguardian.com/uk-news/2017/jun/15/grenfell-tower-fire-teenage-survivor-exam |
| 01:02 | Fire Brigade enter south lift at ground level, rise to Level 2. Lift door held open by fire hoses. | NORTHLEIGH/Op Northleigh Spread of Fire/Interactive/CCTV/Southlift.mp4 |
| 01:04 | Tiago Alves: “Me and my sisters ran down the stairs. My dad stayed upstairs and he was knocking on the neighbours’ doors.” | https://www.theguardian.com/uk-news/2017/jun/15/grenfell-tower-fire-teenage-survivor-exam |
| | CCTV shows Ines and Tiago Alves exiting the building | MET000080463 |
| 01:08 | CCTV shows Miguel Alves exiting building with others – possibly Level 13 occupants | MET000080463 |
| 01:14 | Fire spreads from Flat 16 window to external cladding | MET00006589 |
| 01:21 | LFB 999 call: Flat 195 (Level 22): Caller describes smelling smoke “from the lift side”. Advised to “stay inside and keep your door and windows shut.” | Reference to be confirmed. |
| 01:22 | Occupants seen moving (presumably evacuating) from 7 th floor. No smoke visible in lift lobby. | NORTHLEIGH/Op Northleigh Spread of Fire/Interactive/CCTV/7 th floor.mp4 |
| 01:24 | LFB 999 call: Occupant in Flat 96 (Level 12) indicates that fire has spread internally through the kitchen window: Says “I can’t breathe’ and that the “the fire is in the kitchen!” | Reference to be confirmed |
| 01:25 | LFB 999 call: Occupant in Flat 111 (Level 14) unable to egress due to smoke in lift lobby: Caller says ‘it’s [the fire] coming right past my window from next door.” There is fire “all on my side” but it is not inside the flat. The caller can smell smoke. There is smoke coming into the flat from the landing. Caller says that he has “tried to open the door and there’s a lot of smoke”. | LFB00000308 |
| 01:26 | LFB 999 call: Neighbour from Flat 95 (Level 12) confirms fire in Flat 96, with smoke outside. The caller states her | LFB00000309 |

| Time | Action | Evidence |
|-------|---|--|
| | neighbour has had a fire in the kitchen already and says smoke is “coming through the floor - from our main door because it’s outside.” | |
| 01:27 | CCTV footage shows two occupants arriving at Ground Level using the north lift (the south lift at this time is being held at Level 2). Smoke spills into the lobby as occupants exit. As the occupants open the door to the lift lobby, rush of make-up air causes smoke to be drawn back in to the lift shaft. This occurs again when a firefighter opens the same door to enter the lift lobby. | NORTHLEIGH/Op Northleigh Spread of Fire/Interactive/CCTV/Lift lobby.mp4 |
| 01:28 | LFB 999 call: 3 Occupants from Flat 82 (Level 11) unable to egress due to smoke in lift lobby: Caller states she is stuck on the 11th floor and does not know how to get out. Asked if there is any smoke coming into the property, the caller responds, “Not at the moment but if I open the door there’s smoke on the landing.” There are further 999 calls from Flat 82 at 01:33 (states no smoke in flat but it is getting worse outside, asks for assistance in evacuating), 02:02, 02:18, 02:32 (no smoke coming in), 02:37 (flames on landing), 02:44 (smoke coming through windows and fire coming through kitchen window), 03:00, 03:03, 03:04, 03:13 & 03:32 (fire in flat, egress not possible due to smoke). | LFB00000307 LFB00000313 LFB00000338 LFB00000347 LFB00000360 LFB00000367 LFB00000377 LFB00000393 LFB00000394 LFB00000401 LFB00000410 LFB00000425 |
| 01:29 | LFB Call: Caller in Flat 201 (Level 23). Confirmed as Jessica Urbano Ramirez. The call lasts 55 minutes. Jessica states that she came out of her house because of the fire. She is now in a group of 10 in a bedroom in a flat on the top floor. The fire is in the living room. Jessica describes smoke coming from “everywhere” including the floor. People have tried to go outside but there was a lot of smoke. The operator refers to a smoke alarm making it difficult to hear. Jessica says more than once that she and others ‘can’t breathe’. She confirms seeing “flames coming up through the window”. Later she says that fire is “coming through the window” and that the window is on fire.. | LFB00000507 |
| 01:30 | LFB 999 Call: Caller on Level 23: states “we are all stuck on the top floor and the doors [presumably to the roof] won’t open”. Caller continues that there is smoke everywhere and the fire is in our house on the 22nd floor. Everyone is now on the 23rd floor. Caller states the fire had “broken into the kitchen of our flat” and she had run into the neighbour’s flat. | LFB00000310 |
| 01:30 | LFB 999 Call: Caller on Level 22. States it is “terrible up” here and “you can’t see your hand in front of you.” Caller advised to put towels down to stop smoke coming in. | LFB00000459 |
| | LFB 999 Call: Caller on Level 22 states she is in her neighbour’s house and her neighbour says the fire is from the 11th floor. There is smoke now everywhere. | Reference to be confirmed. |

| Time | Action | Evidence |
|-----------------|--|--|
| 01:30 | LFB 999 Call. Caller is in Flat 175 (Level 20) with her husband and 3 children. The caller indicates that the fire is “in my neighbour’s.” She reports that smoke is coming into her flat. Her husband has blocked the doors and the family is now in the living room. Caller states she is “really scared” and “panicking.” She has seen the flames and can smell smoke. | LFB00000314 |
| 01:33 | LFB 999 Call: Caller from Level 11 says “Please, please, the fire is inside of my flat.” He continues that “it’s inside of the room.” | LFB00000312 |
| 01:34 | LFB 999 Call: Occupant in Flat 192 (Level 22) states “we are trapped in 192 ...” and continues “ We couldn’t get down the stairs, because the stairs is full of smoke. ” Operator advises the caller to close doors and windows to keep the smoke out of the flat. | LFB00000315 |
| 01:36 | NWFC 999 Call; Occupant in Flat 9 (Level 3) . The caller is identified as Mariko Toyoshima-Lewis. She explains that as a wheelchair user she is unable to self evacuate. Mrs Toyoshima-Lewis reports that she can see smoke coming into the flat. Operator confirms that information has been passed to the fire crews. The call ends with the arrival of fire fighters to assist evacuation (exit building at 2:10 am). | LFB00000506 |
| 01:38 | LFB 999 Call: Caller is in Flat 205 (Level 23) . 7 persons in the flat altogether. The caller confirms that no smoke is coming into the property but adds “but our flat was underneath, and that -- there was no smoke in there. It was absolutely fine, but then all of a sudden the flames just blew into our kitchen --”. [See call from Level 23 timed at 01:30 above]. | LFB00000317 |
| 01:38 | LFB 999 Call: Occupant in Flat 95 (Level 12) , reiterates fire is in neighbour’s flat (Flat 96), implies that smoke is in lift lobby. Additional calls are made from the same flat at 01:44 (embers have come through window and started fire in kitchen of Flat 96), 01:54 (caller reports that surrounded by fire - next door, on the “landing” and near the lift, below and on the flat windows. Describes the smoke in the flat as “terrible”. At the end of the call the flat occupants are advised to leave and appear to encounter fire fighters on doing so). | LFB00000318 LFB00000324 LFB00000332 |
| 01:37- 01:38 | Fire brigade re-enter south lift, rise to smoke effected floor at Level 11 or Level 12, discharge onto smoke-filled lobby. | NORTHLEIGH/Op Northleigh Spread of Fire/Interactive/CCTV/Southlift.mp4 |
| 01:38 | Rania Ibrahim (Flat 203, Level 23) starts Facebook Live videos which shows the corridor filled with black smoke, very limited visibility around the time that an increase of smoke is observed on the 7 th floor lobby. | Facebook Live |
| 01:38 | LFB 999 Call. Caller is in Flat 115 (Level 14) . She is alone with her baby. Reports smoke is coming in under the front door and through the windows. Advised to block the door and | LFB00000321 LFB00000331 |

| <i>Time</i> | <i>Action</i> | <i>Evidence</i> |
|-------------|--|--|
| | close windows. Caller cries, "there is fire coming from the door". The call appears to end abruptly. Occupant calls back at 01:48. Asked if there is a room without smoke, caller replies, "All of them have smoke..." The smoke is coming in through the door the windows. She confirms she has already blocked the door and closed the windows. | |
| 01:40 | Reduced visibility in Level 7 lift lobby. Occupants evacuated with assistance from firefighters. | NORTHLEIGH/Op Northleigh Spread of Fire/Interactive/CCTV/Lift lobby.mp4 |
| 01:40 | LFB Call. Occupant in Flat 111 (Level 14) . Caller states he is on his own and his "whole flat is full of smoke." The smoke is coming in through the windows and the door. Caller has locked himself in the bathroom. The operator advises him to put towels around the door to stop smoke coming in. | LFB00000322 |
| 01:41 | LFB 999 Call. Occupant in Flat 73 (Level 10) : asked if there is smoke in the flat, the caller says "...there's smoke coming up and the door [to lift lobby] is completely hot. Advised to stay in flat and block the door to stop any smoke coming in. | LFB00000319 |
| 01:44 | LFB 999 Call. Occupant of Flat 95 (Level 12) states that "fire embers have started a fire in the flat next door ... it's come up through the windows, it's gone into number 96". The kitchen of 96 is on fire. The caller states that smoke is coming in to his flat and that it is "really smoky in here" and "someone's trapped on 11th floor". | LFB00000324 |
| 01:47 | LFB 999 Call. Two callers from Flat 74 (Level 10) : Caller 1 says they are still "inside", asks how they are going to get outs and then says that they are going outside. Caller 2 then comes on the line. She confirms to the operator that they "can't leave because there is smoke in the corridor, but people are leaving." Call again at 02:00 (asking for further advice - smoke still coming in - and told to put sheets and towels down). Follow up calls from relative outside the building at 3:53 (reporting that there are two adults in the flat, the flat door is jammed and so they can't get out) & 4:10 (caller reporting that the occupants of Flat 74 are now in the staircase) | LFB00000330 LFB00000336 LFB00000592 LFB00000600 |
| 01:50 | LFB 999 Call. Caller from Flat 194 (Level 22) . Occupant says smoke is coming into the flat and he can't see anything. The operator advises that he close any windows, block doors and and stay low. 02:00: a further call from Flat 194. Caller says he has been waiting for 15 minutes. He says the flat is "worse. It's black | LFB00000328 LFB00000337 LFB00000695 LFB00000352 LFB00000395 LFB00000407 |

| Time | Action | Evidence |
|------|---|----------|
| | <p>in here. I can't see a thing". He is a pensioner and "can't get about." He mentions that his letterbox won't close and is advised to block it with a towel.</p> <p>2:24: Call from Flat 194. Caller says "I'm so fucking frightened up here! ... 45 minutes I've been in my flat ... I'm jumping out the window..."</p> <p>3:01: Call from Flat 194. Male says "Please come and get me". Says he is not able to get out of the property. "Its too dark, it's too hot." He confirms that the fire is "next door" and says "it's on the other side as well." Advised by operator to wrap himself in sheets and towels and get out. The caller asks for someone to come up and get him but then the call is cut off.</p> <p>3:10: Surrey Fire & Rescue call LFB. Surrey have just spoken to the family of the occupant of Flat 194. Surrey reports that there is so much smoke and flame that he cannot get out of the flat - "He is literally going to be running through flame -". LFB advises Surrey to tell people to just get out.</p> | |

2673

2674 **TABLE 5: BASIS FOR THE FIRST HOUR OF THE INTERNAL SMOKE SPREAD TIMELINE**

2675

2676 The compilation of 999 calls, including those presented in Table 5, is summarised in Figure 68 and Figure 69.
 2677 There is still a large amount of data in the form of firefighter statements, surviving residents statements, and
 2678 (albeit coarse) camera footage that could, when combined, allow for a more complete picture of internal fire
 2679 spread and smoke migration.

2680 Figure 68 shows that smoke was reported for the first time in the lobby area in 11th to 14th and 24th floors
 2681 approximately 30-35 minutes after the first 999 call. Figure 70 shows that at approximately the same time,
 2682 internal fires were reported on the 12th and 22nd floors. The fire on the 12th floor is in Flat 96, directly above
 2683 the flat of fire origin. This flat was reported on fire at 01:24. The location of the flat on the 22nd floor is not
 2684 identified in the 999 call transcript.

2685 General Area of the Flat 96 - 12th floor fire:

- 2686 • At same time as report of fire on 12th floor (01:24), 14th floor occupant reports lobby as impassable
 2687 due to smoke.
- 2688 • Within two minutes of call from occupant of 12th floor fire flat (01:26), 12th floor neighbour reports
 2689 smoke coming from outside the main door of flat 96. This implies 12th floor lobby has smoke but not
 2690 flames.
- 2691 • Four minutes after report of fire on 12th floor (01:28), smoke reported on 11th floor landing that is
 2692 preventing occupant from leaving.

Given the timelines and fire characteristics required for door damage, it is clear that early smoke migration (01:24 to 01:28) between floors 11th and 14th would have to be through open doors. Figure 70 shows the consequent damage of the area associated to Flat 96. Ultimately, Flat 96 suffered severe damage and the door was found half broken in the doorway. However, smoke is clearly spreading very rapidly in this area and at a rate that is not compatible with the fire induced failure of the entrance door of Flat 96. Therefore, other mechanisms must be responsible for the rapid ingress and spread of smoke. These mechanisms are not immediately clear but appear to have led to a single flat fire compromising the stairwell and lobbies of floors 10 – 14. It is important for Phase Two that, once all evidence is collected, the correlation between physical variables and evidence is considered in more detail.

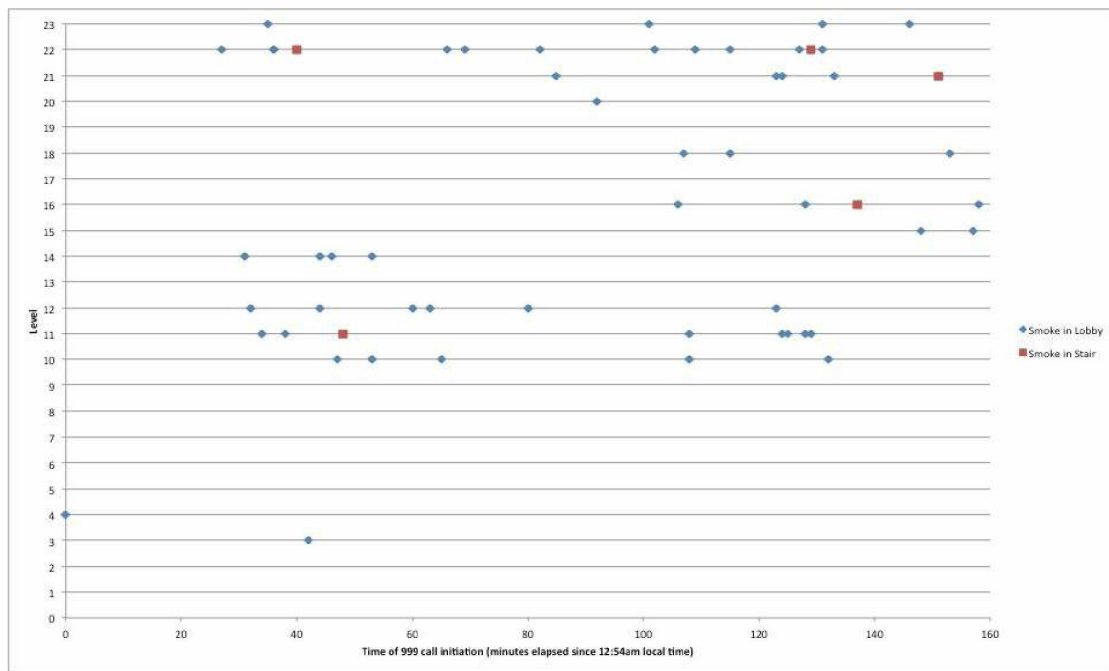


FIGURE 68: LOCATIONS OF 999 CALLERS DESCRIBING SMOKE IN LIFT LOBBIES & SMOKE IN STAIRS. NOTE THAT THE LOCATIONS SHOWN HERE ARE NOT NECESSARILY ON THE SAME FLOOR AS THE FIRE OR SMOKE BEING DESCRIBED BY THE CALLER, BUT INSTEAD THE LOCATION OF THE CALLER AT THE TIME. NO CALLS RECORDED FROM LEVEL 13 CAN BE ATTRIBUTED TO THE EARLY EVACUATION OF LEVEL 13 OCCUPANTS IN THE FIRST 30 MINUTES OF THE FIRE EVENT. ADDITIONAL CALL RECEIVED AT T=251 FROM CALLER ON 10TH FLOOR, DESCRIBING SMOKE IN LOBBY.

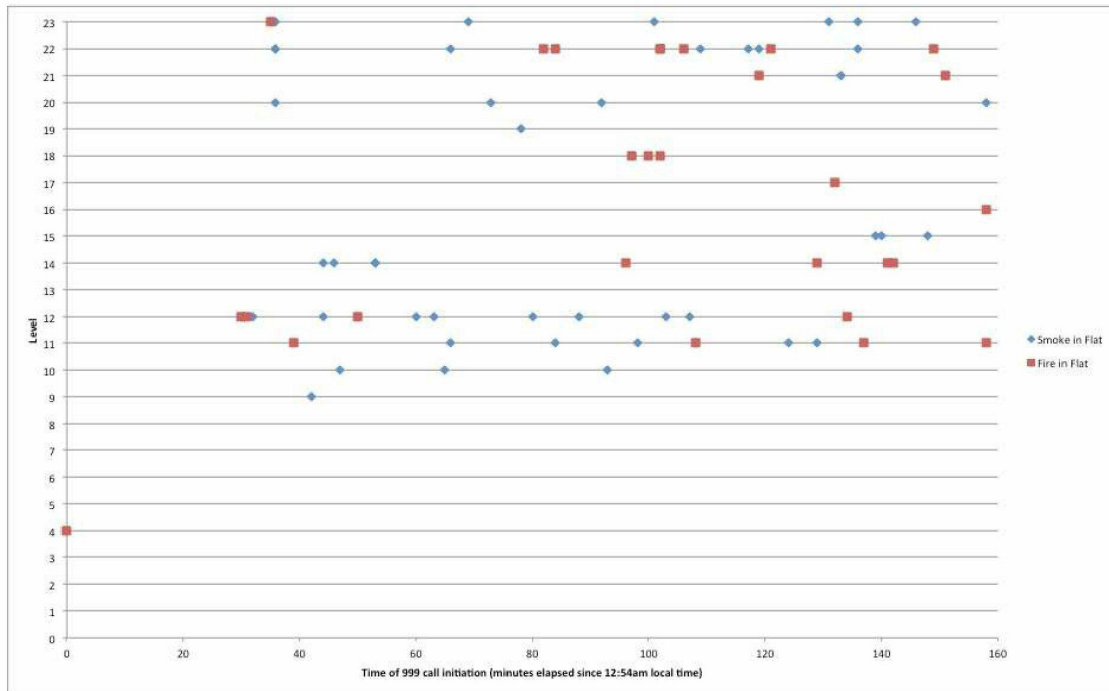


FIGURE 69: LOCATIONS FROM WHICH 999 CALLS WERE MADE DESCRIBING SMOKE AND FIRE IN FLATS. NOTE THAT THE LOCATIONS SHOWN HERE ARE NOT NECESSARILY ON THE SAME FLOOR AS THE FIRE OR SMOKE BEING DESCRIBED BY THE CALLER. PLOT DOES NOT CAPTURE CALL DURATIONS; FOR EXAMPLE, CALL FROM LEVEL 23 AT T=35 LASTS FOR 55 MINUTES, NOT KNOWN AT WHAT TIME DURING CALLER DESCRIBES FIRE IN FLAT. NO CALLS RECORDED FROM LEVEL 13 CAN BE ATTRIBUTED TO THE EARLY EVACUATION OF LEVEL 13 OCCUPANTS WITHIN THE FIRST 30 MINUTES OF THE FIRE EVENT. ADDITIONAL CALL RECEIVED AT T=251 FROM CALLER ON 10TH FLOOR, DESCRIBING SMOKE IN FLAT.



FIGURE 70: FLAT 96 AS VIEWED FROM THE LEVEL 12 LOBBY, WITH BROKEN FRONT DOOR VISIBLE IN DOORWAY

5.3.4 ONSET OF GENERAL UNTENABLE CONDITIONS

At some point during this third stage of the fire, as more and more compartment fires were ignited, and smoke migrated into the egress paths and unaffected flats, general conditions within the building can be deemed to have become untenable²⁵. Figure 68 and Figure 69 show the increase in calls reporting smoke and fires in units as well as smoke in the lift lobbies and stairs.

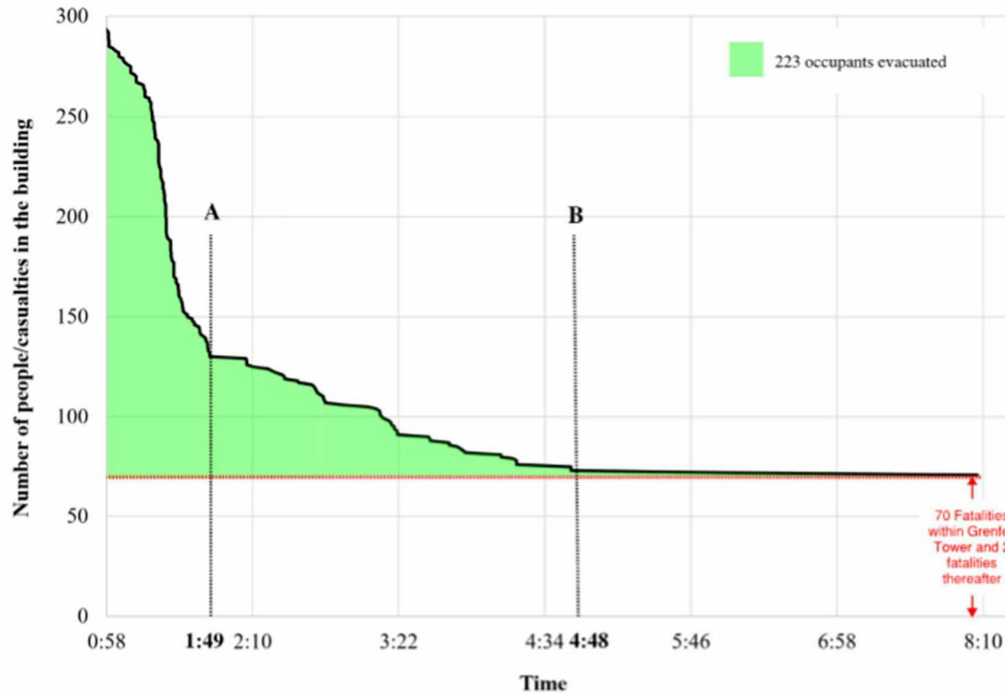


FIGURE 71: NUMBER OF OCCUPANTS IN GRENFELL TOWER DURING THE FIRE EVENT FROM [4].

Dr Lane's Phase One expert report [4] shows an overview of the number of people remaining in the building over time from the onset of the fire (Figure 71). The rate of evacuation slowed significantly at 01:50. At this point the fire has reached the East elevation windows of approximately 25 separate flats, and the North elevation windows of approximately 9 of those same flats (Figure 72). In this first hour of the fire most of the calls reporting smoke are localized in areas where the fires have been observed to breach the external envelope of the building (Floors 11th to 16th and 22nd and above). Given the significance of the external spread on all subsequent events potentially leading to the involvement of the compartment and then the breaching of the unit, the consistency of all this information is as expected.

²⁵ See footnote (1) for approximate times for each stage.

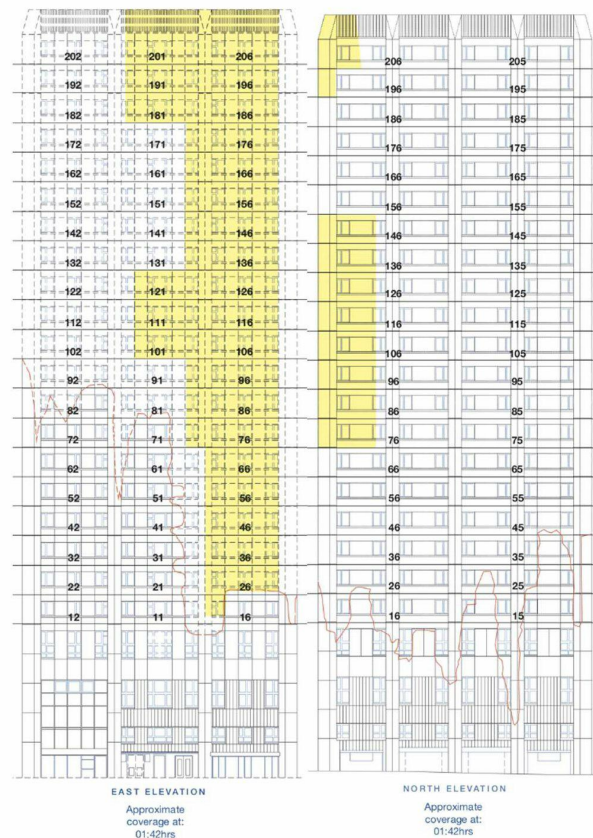


FIGURE 72: APPROXIMATE EXTENT OF EXTERNAL FLAME SPREAD AT 01:42 AM, THE TIME OF THE INITIAL SIGNIFICANT DECREASE IN THE RATE OF PEOPLE EGRESSING THE BUILDING NOTICEABLY DECREASED.

5.3.4.1 INTERPRETATION

During this stage of the fire, the smoke was passable by firefighters with Breathing Apparatus (BA), and as shown in Figure 71 (adapted from Figure 14.17[4]), during this period at approx. 01:50, occupants stop evacuating the building. At this point, there was a period of approximately 20 minutes where no egress took place. At 02:06 the fire was declared a major incident and from this point, egress appears to have resumed however at a much lesser rate than before. The reasons for this are unclear.

Up to 02:45, 1/3rd of the 80+ calls had come from Levels 22 and 23 and another 1/3rd had come from Floors 10 – 12 suggesting these areas in particular were unpassable. Firefighters issued an official end to the “stay put” guidance and initiation of evacuation of remaining residents at 02:47, however they had been in a search and rescue mode prior to that.

The rapid decrease in egress of occupants at approximately 01:50 corresponded with the fire spreading laterally to the central panel of the east elevation and to the North elevation. Egress paths from the floors around Level 12 and above Level 20 had become unpassable, evolving from sporadic, localised unpassable areas at the start of Stage 3 to blocks of unpassable levels by this time. Therefore, the time range 01:50 – 02:00 is considered to mark the onset of generalised untenable conditions and the beginning of Stage 4.

5.4 ASSESSMENT OF CHARACTERISTIC STRUCTURAL HEATING DURING STAGE THREE

Heating of the structure is briefly assessed here to provide an indication of the likely impact of a typical compartment fire on the Grenfell Tower structure. The intent is not to provide an assessment of structural stability, but to give a baseline assessment purely based on a thermal analysis. This assessment utilises the temperature of the reinforcing steel (rebar) in the slab to make a crude assessment of any impact compartment fires might have had on load bearing capacity. Details of the analysis are provided in Appendix F. Two scenarios are evaluated, the presence of a post flashover compartment fire and heating via the external fire.

Information available at present is limited to the depth of the slab, indicated as 200mm in [SEA00000271] and [43] with a 50mm screed on the top side. The rebar depth is not known exactly at the present time. Coring results reported in [43] imply that the rebar could be located between 25 – 35mm from the slab underside, and a minimum concrete cover of 25mm is typically required in order for rebar to act effectively [44]. A 1D heat transfer model of a typical roof slab is developed. From this model, the temperature of the rebar in the slab can be evaluated and the time to reach onset of loss of strength is established.

The model assumes that the rebar temperature can be conservatively approximated as the temperature of the concrete between 25mm and 35mm depth in to the concrete slab [44]. The gas phase temperature was taken as having a lower bounding value of 850°C and an upper value of 1000°C as estimated in Section 5.4. A conservative estimate for the onset of the rebar degradation is 300°C so this will be taken as a lower bound failure criterion, while 550°C is more commonly taken as a failure condition for the rebar, this will be used as the upper bound failure criterion. The plot in Figure 73 presents the results of the two heating regimes implemented. The results are summarised in Table 6.

| Bound | 25mm - 300°C | 25mm – 550°C | 35mm - 300°C | 35mm – 550°C |
|-------|--------------|--------------|--------------|--------------|
| Upper | 28 mins | 120 mins | 40 mins | 161 mins |
| Lower | 40 mins | 220 mins | 54 mins | 286 mins |

TABLE 6: THE TABLE GIVES CHARACTERISTIC TIMES TO HEAT THE REBAR AT 25MM AND 35MM DEPTH, TO TEMPERATURES OF 300°C AND 500°C, UNDER UPPER BOUND (1000°C) AND LOWER BOUND (850°C) GAS PHASE EXPOSURES. TIMES TO REACH THE ONSET OF LOSS OF STRENGTH ARE IN THE RANGE OF 30 – 60 MINUTES. TIMES TO REACH THE TYPICAL CONSERVATIVE DESIGN FAILURE CRITERIA OF 550°C ARE IN THE RANGE OF 2 – 5 HOURS.

The first flat unit fires ignited due to re-entry of the fire from external flame spread are reported as beginning at approx. 01:20-01:30. This stage of the fire lasts until approx. 02:00, a maximum of 40 minutes after these fires ignited. Given the structural heating timescales calculated above, it is estimated that the structure is not at risk during this stage of the fire as the rebar in the concrete slabs of the first flats to catch fire will at most only be beginning to approach temperatures at which its strength is affected. This also does not account for the time associated with the fire growing to this fully-developed phase.

This conclusion is further endorsed by Buchanan [44] who states that, “Catastrophic failures of reinforced concrete structures are rare, but some occasionally occur. Observations have shown that when concrete

buildings fail in real fires, it is seldom because of the loss of strength of materials.” Thus, the approach used here can be considered as being very conservative.

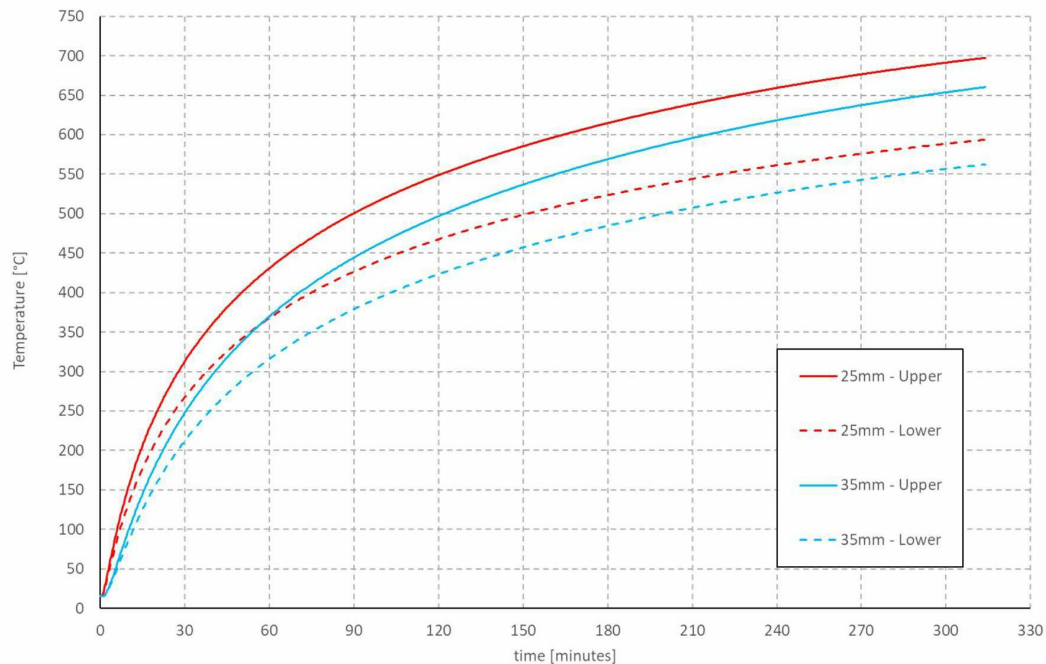


FIGURE 73: HEATING CURVES FOR SLAB REBAR LOCATED AT 25MM AND 35MM ABOVE THE BASE OF THE CONCRETE SLAB FOR UPPER BOUND (1000°C) AND LOWER BOUND (850°C) GAS PHASE TEMPERATURE EXPOSURES.

Given that the characteristic times of impingement of external flames on the interior slabs will be less than 25 minutes at this stage, it is clear that this mechanism of heating would also not impact the global stability of the structure. This is due to the short exposure time, the expectation that the temperature of the impinging flames will be no greater than the values assessed above, and the fact that the heat application is typically only localised around the window (see Section 5.3.2.1).

5.5 COMPLIANCE ISSUES AFFECTING THE CHARACTERISTICS OF STAGE THREE

At this stage, the building is experiencing a fire for which it was not designed. The building envelope was not designed to withstand an external fire emerging from the building itself, thus the failure of the different components of the window system that allow for penetration of the fire into the building cannot be explained solely by compliance issues. There are clearly stronger and weaker elements and many of the weaknesses are associated with poor quality design and/or construction; issues which are important when considering recommendations for improvements in construction practice. Nevertheless, in the case of the Grenfell Tower fire, the failure of the window system will have happened by one path or another. It is not possible to establish a detailed sequence of failure (it will vary from unit to unit) but what is clear is that, given the high heat fluxes, all failure paths would have manifested within a very narrow period of time.

Once the fire has re-entered the building, compartmentalization is the main line of defence. Compliant systems would have helped to protect egress paths and deliver safe paths for the occupants to evacuate. While the external fire contributes to ignition of the unit furnishings, the energy contribution to the unit is limited and localized to the areas around the window. Thus, there is no reason for compartmentalization requirements designed to withstand a post-flashover fire, not to be capable of withstanding a fire of the nature of that in Grenfell Tower.

Occupant behaviour (leaving doors open) or firefighting operations most likely had an impact on the capability of smoke and flames to migrate from the units towards the lobby and stairs. Nevertheless, this possibility cannot exonerate the need for compliant compartmentalization features (walls, fire doors, fire stop, etc.).

The design of the lobby and single stair egress called for greater redundancy by means of a smoke management system. The system was not designed to manage the smoke generated by fires in multiple units, therefore the performance of this system could have not been guaranteed given the nature of the Grenfell Tower fire. Independent of the conditions of the smoke management system for Grenfell Tower, it is important to revisit the compliance requirements for ventilated lobbies if the scenario of external fires is to be considered.

5.6 SUMMARY

- The third stage of the fire begins at approximately 01:30 when the external fire propagation reaches the top of the building and begins to spread laterally.
- The principle mechanism for lateral spread of fire around the external cladding of Grenfell Tower was via the architectural crown.
- Burning molten materials and debris fell from the top down, collecting on horizontal shelves and initiating new fires which then spread back up the building. These fires will progress upwards towards the fire that originated them, further up the building.
- This was more prominent higher up the building as lateral expansion of the smoke plume from fires lower down the adjacent façade resulted in more generalised pre-heating of the upper parts of the façade, aiding their subsequent ignition and downward spread.
- A fire that is capable of spreading over the surface of the façade system will impose sufficient fluxes of heat, that breaching of the façade at window locations is inevitable, regardless of the detailing of the window and its surroundings.
- Once fire has re-entered it may act as an ignition source resulting in a fire that may or may not result in flashover.
- Adequate compartmentalization would be expected to restrict any resulting fire to that unit. This is valid for a single unit fire and there is no reason why it should not be valid for a fire that spreads externally.
- Early internal spread of smoke on and around floors, where early ingress of the external fire led to compartment fires, implies compromised performance of internal compartmentalization.
- Fire induced compromise of the integrity of the flat doors would have required a post-flashover fire based on the subsequent testing of doors by the BRE. The brief period of time until loss of compartmentalization in Stage 2 and Stage 3 (as evidenced by smoke appearing in west and south facades) is not consistent with the longer timescales associated with the fire induced failure of the

2854 doors. It is therefore very likely that doors were left open allowing free migration of some through
 2855 undamaged doors.

- 2856 • Analysis of emergency calls and firefighter statements indicate that communal lobbies and stairwells
 2857 in the middle of the building (Levels 10-14) and at the top of the building (Level 20 and above) rapidly
 2858 became either actually, if not seemingly, impassable to occupants on and around those levels by
 2859 approximately 01:50.
- 2860 • This rapid spread of smoke points to human factors (actions on the day, or in the design and
 2861 maintenance) hindering the performance of the compartmentalization. The exact form of this
 2862 involvement is unclear based on the available evidence however possibilities include:
 - 2863 ○ Doors to flats with compartment fires being left open / door closers removed.
 - 2864 ○ Firefighter intervention damaging flat doors through forced entry / holding flat and stair doors
 2865 open to enable passage of hoses for direct intervention.
 - 2866 ○ Poor design of compartmentalization, primarily doors, since no evidence has been found of
 2867 inadequate walls.
 - 2868 ○ Poor implementation of fire stopping during construction and subsequent renovations /
 2869 works. Nevertheless, no significant evidence of poor practise has been found
 - 2870 ○ Any use of the lift.
 - 2871 ○ Smoke ventilation shaft.
- 2872 • In general, the timeline of egress of occupants, reports of smoke and fire locations, and the actions
 2873 and locations of firefighters are not well understood at this stage, based on the available evidence.
 2874 This information is crucial to identifying the mechanisms by which smoke was able to migrate to, and
 2875 through, the core of the structure so rapidly. Work on correlating physical evidence with testimony
 2876 should continue in Phase Two.
- 2877 • An analysis of the effect of compartment fires on the structural stability of the floor slabs indicates
 2878 that the floors would have maintained structural integrity during this Stage.
- 2879 • The third stage ends at approximately 01:50 – 02:00 when general conditions throughout the building
 2880 can be considered untenable.

2881

2882

2883

6 STAGE FOUR: UNTENABLE CONDITIONS IN THE BUILDING

There is not much that can be said about this stage of the fire beyond what has been described in detail in Dr Lane's Phase One expert report [4]. This section will therefore focus simply on establishing any indication of tenability and a post event final damage assessment. At this stage, the fire has involved a very large number of units, compartmentalization has been breached at multiple levels and firefighting capabilities have been significantly exceeded by the event. Conditions in the building are difficult to establish but it is clear that a significant part of the building is untenable. Egress potential has diminished dramatically, as clearly indicated by the slow rate of evacuation of building occupants. The following provides an indication of overall tenability based on the location and movement therein of casualties from the fire. Post fire damage assessment provides further information on the conditions within the building at this later stage of the fire.

6.1 LOCATION OF CASUALTIES

Based on the DVI Reconciliation Unit final floor plan of recoveries from Grenfell Tower [MET00008018], the location and movement of casualties based on their apartment of origin and their end location was tabulated. Figure 74 shows a visualisation of casualties found on the same level on which they were known to have lived.

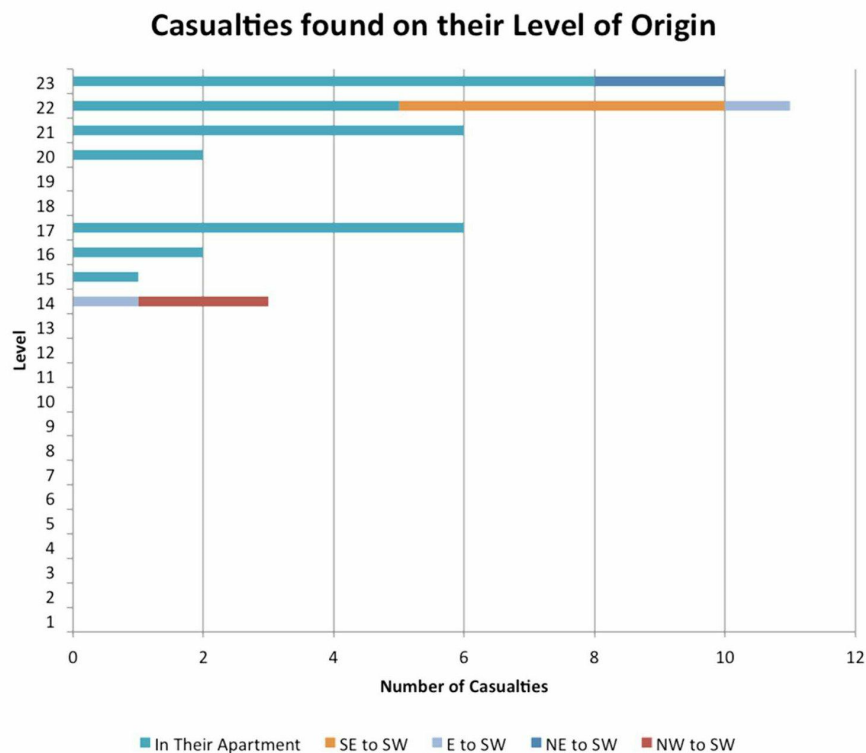


FIGURE 74: VISUAL REPRESENTATION OF CASUALTIES FOUND ON THE SAME LEVEL AS THEIR APARTMENT OF ORIGIN. IN SOME INSTANCES, CASUALTIES MOVED Laterally FROM THEIR OWN APARTMENT TO APARTMENTS IN THE SOUTHWEST CORNER OF

THE BUILDING (APARTMENTS '3'). THE SOUTHWEST CORNER OF THE BUILDING WAS THE LAST CORNER TO BE DIRECTLY EXPOSED TO EXTERNAL FLAME SPREAD ON THE BUILDING FAÇADE.

While most casualties were found within their apartment of origin, twenty-nine (29) casualties were found in other locations. Their movement is visually represented in Figure 75.

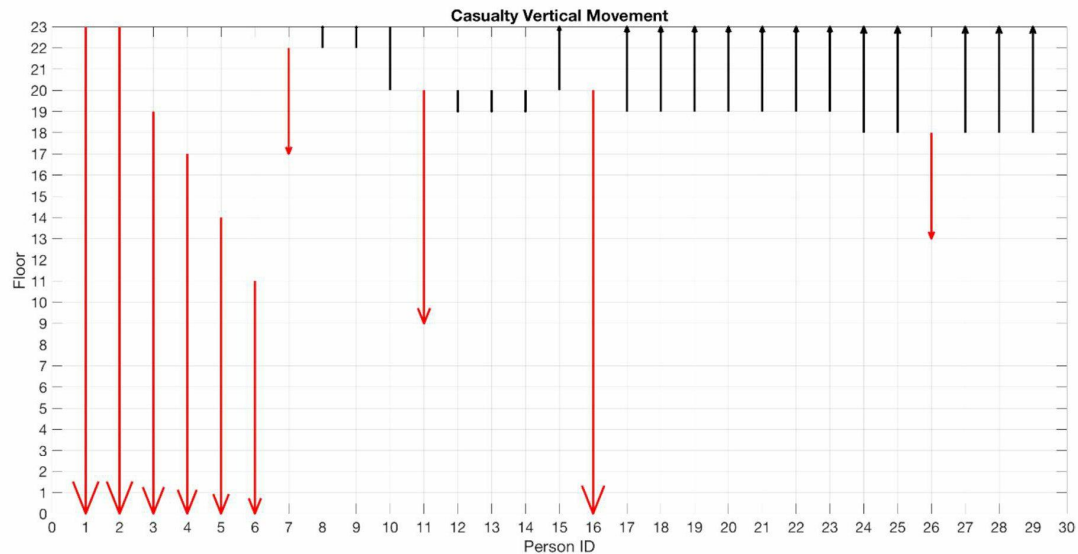


FIGURE 75: VISUAL REPRESENTATION OF CASUALTIES FOUND ON A FLOOR OTHER THAN THE ONE OF THEIR OWN FLAT. DATA SOURCED FROM MET00008018. 19 CASUALTIES WERE ABLE TO REACH THE EXIT STAIR BUT PROCEEDED UPWARDS RATHER THAN DOWN THE STAIR. 3 CASUALTIES WERE FOUND EITHER IN THE STAIR OR IN ADJACENT LOBBIES, SUGGESTING THEY ATTEMPTED TO TRAVEL DOWN THE EGRESS STAIR.

There is a clear cut off above Levels 12 – 13 where the vast majority of occupants living on or below these floors survived. Above these levels fatalities are grouped into two distinct bands.

The number of casualties immediately above Levels 12-13 corresponds to these levels being unpassable relatively early on in the event. Below these levels, all people escaped or were rescued. Immediately above these levels (14 – 17), occupants/casualties don't appear to have been able to move up or down. This is evidenced in the statements of firefighters which describe a sustained effort from the onset of Stage Four onwards, to extinguish and climb beyond Levels 12 and 13. There are limited reports of firefighters accessing the upper floors prior to this [MET00005348, MET00005590, MET00005350, MET00005384] however these appear to be isolated incidents during earlier stages of the fire.

By 02:05 [MET000080602] it is already documented that getting beyond these floors is presenting a significant difficulty. Numerous accounts of the building being clear up to the 12th floor and firefighting teams being sent to the 12th floor to extinguish fires are available [MET00007520, MET00005357, LFB00000007] spanning times estimated to be as late as 08:30. Typically, firefighters report a lack of water pressure when trying to extinguish fires on this floor. Numerous other statements [MET00005437, MET00005299, MET00005478] with unclear

timings report attempts to firefight and search and rescue on these floors that were impeded by consistent high levels of dense smoke and heat.

At some stage (unclear) Levels 18 – 19 also appear to have been untenable to the point that occupants from these levels attempted to move up or down the building. This would also explain why occupants/casualties were found in Levels 14 – 17, located between regions of untenability.

Above Level 20, occupants/casualties were prevented from moving downwards early on and either remained in their flats, moved to the SW corner flats, and / or moved to the 23rd floor (potentially to try and access the roof of the building) where they remained trapped.

While rescue operations continued throughout the first hours of this stage, it is unclear from exactly where these rescues took place. The dynamic location of the bridgehead does however provide some indication as to the levels which firefighters were able to reach. The following diagram (Figure 76) adapted from [4] can be used to illustrate this movement.

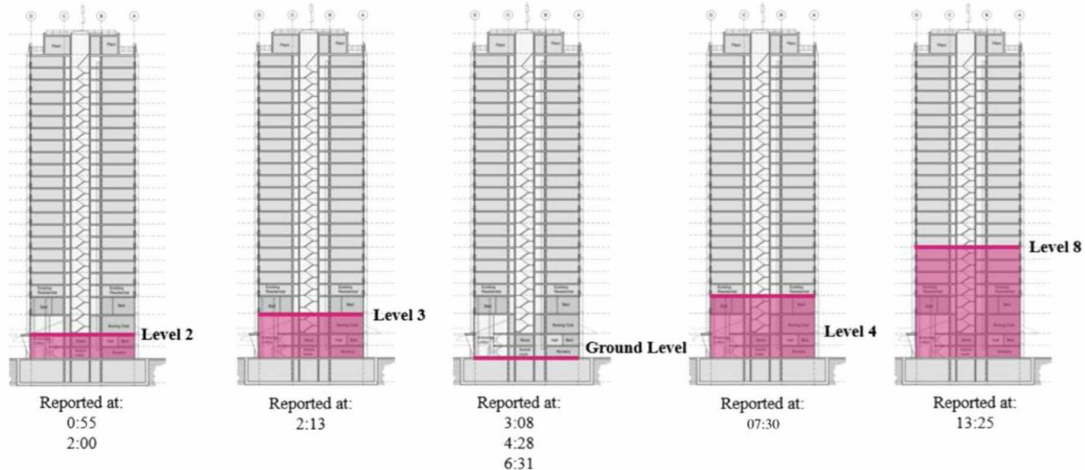


FIGURE 76: LOCATION OF THE BRIDGEHEAD THROUGHOUT FIREFIGHTING ACTIVITIES AT GRENFELL TOWER [4].

The diagram shows that, following the onset of generalised untenable conditions, firefighters were attempting to move up the building however were soon forced back down due to smoke concentrations as far down the building as Level 3. The implications of the extent of usable duration of breathing apparatus would mean that the firefighters were generally operating at lower levels over this period of time, therefore rescue operations would likely have been concentrated beneath Levels 10-12.

6.2 POST-FIRE STRUCTURAL ASSESSMENT

An assessment of images taken of all flats within the tower post fire have been assessed and categorised according to the level of damage. A summary table of this assessment is provided in Appendix G. Damage is grouped in to five categories:

- No damage
- Minor: Smoke damage only i.e. soot ingress through windows / doors

- 2953 • Moderate: Smoke and partial fire damage
- 2954 • Severe: Significant structural damage and spalling
- 2955 • Major: Post-flashover fire conditions

2956

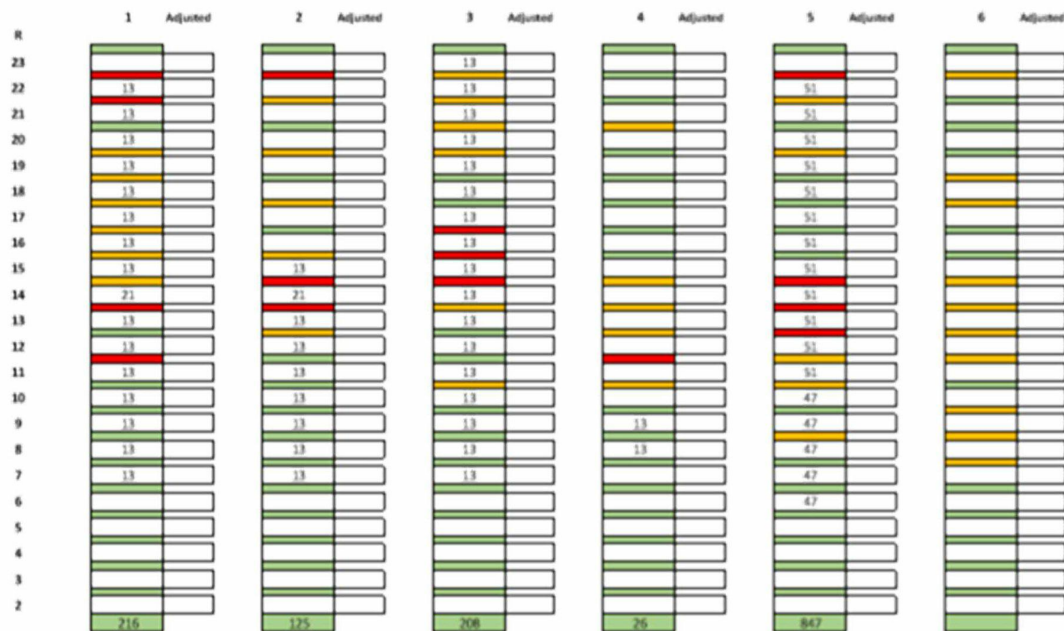
2957 All 10 instances of no damage occur from the 8th floor down with 6 of those on the lowest 2 levels. There are
 2958 15 instances of minor damage from the 10th floor down. Other than 1 flat on each of the 11th and 12th floors
 2959 which have moderate damage, and 2 flats on the 11th and 1 on the 12 that have severe damage, all other flats
 2960 from Level 11 upwards experienced major damage. All flats above the flat of fire origin experience severe (2)
 2961 or major (16) damage. Ignition of these flats is likely to have been in the time window represented by Stages
 2962 2 and 3, and the early stages of Stage 4.

2963 From Level 10 upwards, the vast majority of lift lobbies experienced either severe (5) or major (9) damage.
 2964 There is a strong correlation with the number of flats experiencing severe damage and similar damage
 2965 occurring in the lift lobbies. This implies systematic failure of fire doors following post-flashover fires. In most
 2966 cases, fire doors are not visible in the images provided, indicating that they have subsequently been removed
 2967 or were consumed in the fire.

2968 From the 8th floor down, stair doors showed no signs of damage. From the 9th floor upwards, the degree of
 2969 damage to the stair doors ranges from soot on the door (e.g. Level 11) to moderate fire damage on the lobby
 2970 side of the door (e.g. Level 19). The variability in the degree of damage is believed to be a function of smoke
 2971 ingress in the lobby, firefighter interaction with the doors, and internal penetration of flames into the lobby
 2972 area. Unfortunately, not all of the stair doors could be evaluated from evidence provided because they were
 2973 removed from hinges on floors where it is critical to evaluate their performance. It is not clear if the cause of
 2974 this is due to the fire itself, firefighting and search and rescue activities, or subsequent removal of doors for
 2975 forensic testing.

2976 A post-fire structural assessment has been conducted by DeconstructUK [43] followed by shoring up of the
 2977 structure to enable safe inspection of the site. In general, aside from sporadic inconsistencies, the authors note
 2978 that the worst effects of the fire, in terms of structural damage, are found between the 10th to 14th floor. Above
 2979 this, fire damage is extensive but not as serious in structural terms. Below this, damage to the structure is
 2980 typically negligible.

2981 The authors state that, in all but a few locations, the effect of the fire is on the cover (the outer layer).
 2982 Internally, the concrete appears unaffected. This is indicated by assessment of sample cores taken from the
 2983 building. Spalling of concrete columns at 14th, 16th, 20th, and 21st floor levels has left rebar exposed, with
 2984 spalling depths ranging from 35 to 100 mm. In two locations, this reinforcement has yielded. However, the
 2985 authors do not believe this to be a concern in terms of the stability of the structure.



2986

2987 **FIGURE 77: THIS FIGURE TAKEN FROM [43] INDICATES DEGREES OF STRUCTURAL DAMAGE THROUGHOUT THE GRENFELL TOWER.**
 2988 **GREEN REPRESENTS FLATS WITH LITTLE OR NO DAMAGE AND IMPERCEPTIBLE DEFLECTION. AMBER REPRESENTS FLATS WHERE**
 2989 **SPALLING HAS OCCURRED, REINFORCEMENT IS PARTIALLY VISIBLE, AND / OR VISIBLE DEFLECTIONS ARE LESS THAN 100MM. RED**
 2990 **REPRESENTS SPALLING HAS OCCURRED, REINFORCEMENT IS VISIBLE AND DETACHED FROM THE SLAB OR THE SLAB IS IN A**
 2991 **DEGRADED STATE, AND / OR DEFLECTIONS ARE LARGER THAN 100MM. NO EXPLANATION OF THE NUMBERING SYSTEM SHOWN**
 2992 **IN THE GRAPHIC IS PROVIDED.**

2993 Figure 77 provides an overview of the structural damage by floor and by flat extracted from the DeconstructUK
 2994 report [43]. Where slabs are coloured green, this represents flats with little or no damage and imperceptible
 2995 deflection. Amber represents flats where spalling has occurred, reinforcement is partially visible, and / or
 2996 visible deflections are less than 100mm. Red represents spalling has occurred, reinforcement is visible and
 2997 detached from the slab or the slab is in a degraded state, and / or deflections are larger than 100mm. No
 2998 explanation of the numbering system shown in the graphic is provided.

2999 This correlation is assessed in conjunction with observed durations of fires to ascertain if the observed damage
 3000 corresponds to the duration of fire exposure. Select photographs of Grenfell Tower during the fire event were
 3001 sequenced and analysed to identify bounding fire durations internally i.e. the shortest and longest times for
 3002 burning within flats. Figure 78 presents a sequence of photographs of the north elevation from 02:34 am to
 3003 04:43 am. Flats in the northwest corner (numbered “5”, right of centre in photos below) were the subject of
 3004 focus as all northeast corner flats (numbered “6”, on the left of centre) were classified as either “severe” or
 3005 “major” in the post-fire damage assessment, and thus would not have provided a clear delineation between
 3006 short and long duration fires.

3007 Flats 105 and 115, on Levels 13 and 14 respectively, are highlighted in red. These were identified in the
 3008 DeconstructUK post-damage assessment as flats where spalling occurred, reinforcement was visible and
 3009 detached from the slab and the slab was found in a degraded state and/or deflections were larger than
 3010 100mm. These flats are shown to be initially exposed to external flames at 02:34. Flames are visible inside
 3011 these flats through to 04:43. In photos beyond 04:43, these flats were obscured by smoke, making it difficult

3012 to determine the end of burning within these flats. In any case, the available evidence shows that fires burned
3013 internally within Flats 95 and 105 for at least 139 minutes i.e. over 2 hours and 19 minutes. This corresponds
3014 to the analysis in Section 5.4 as falling within the period of time associated with steel reaching a design failure
3015 criteria temperature.

3016 Flats 9, 15, 25 & 35 are highlighted in green. These flats were determined by DeconstructUK to have suffered
3017 little to no damage and imperceptible deflection. As seen in Figure 78, all four flats are shown to be exposed
3018 to external flames at 03:07. Flames are no longer visible in Flats 15 and 25 at 03:44. However, at this time,
3019 flames remain visible in Flats 9 and 35, and are not seen to be extinguished until 04:20. Thus, the available
3020 evidence shows that fires burned internally within Flats 15 & 25 for less than 37 minutes, and within Flats 9
3021 and 35 for less than 73 minutes. This again is in agreement with the results of the heat transfer analysis shown
3022 in Section 5.4, where rebar steel is expected to have reached the range in which its strength is beginning to
3023 degrade, however the slab as a whole still retains sufficient load carrying capacity hence little to no visible
3024 damage and imperceptible deflections.

3025 The appended post-damage assessment, based on the 360 degree photographs, is visually summarized in
3026 Figure 79 below. The flats analysed above are highlighted in red and green below. As can be seen, Flats 95 and
3027 105 suffered severe damage i.e. post-flashover conditions. Flats 15 and 25 suffered minor damage i.e. from
3028 smoke only. Flats 9 and 35 suffered moderate damage i.e. smoke and partial fire damage. Thus, the available
3029 evidence suggests that the duration of fire exposure corresponds with the severity of structural damage
3030 experienced within the impacted compartment.

3031

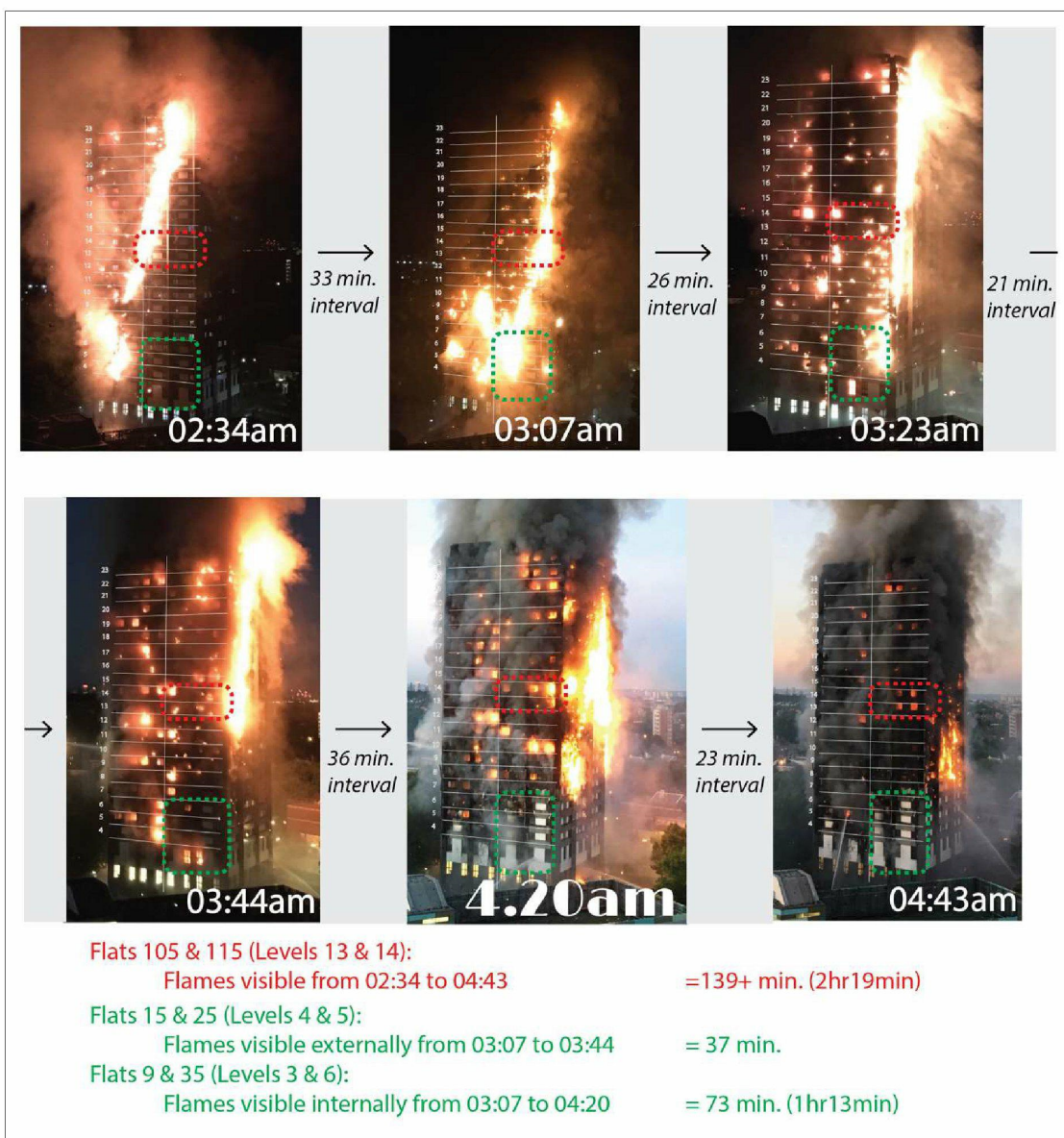


FIGURE 78: A SEQUENCE OF PHOTOGRAPHS OF GRENFELL TOWER NORTH ELEVATION DURING FIRE EVENT. FLATS SHOWING INDICATIVE LONG AND SHORT DURATION FIRES ARE HIGHLIGHTED IN RED AND GREEN, RESPECTIVELY.

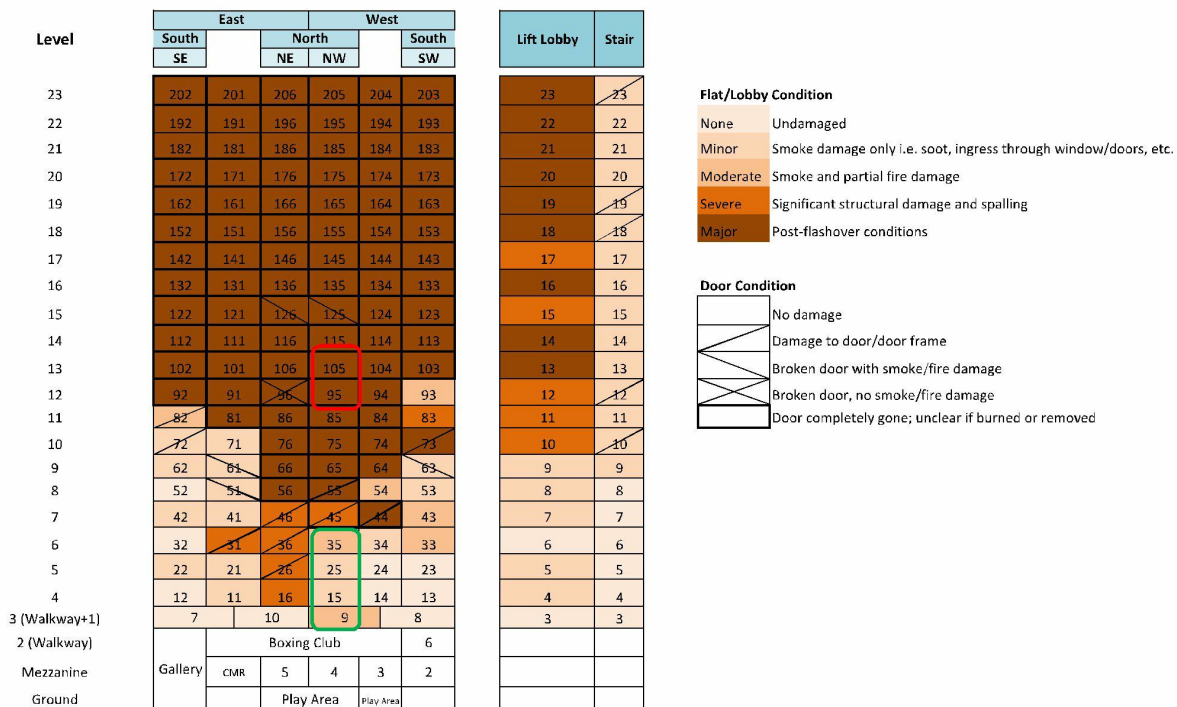


FIGURE 79: GRAPHIC SUMMARY OF POST-FIRE DAMAGE ASSESSMENT INCLUDED IN APPENDIX. FLATS HIGHLIGHTED IN FIGURE 78 ARE HIGHLIGHTED IN RED AND GREEN. NOTE THAT TWO FLATS 9 AND 35 CORRESPOND WITH MODERATE DAMAGE CONDITIONS, WHEREAS FLATS 15 & 25 CORRESPOND WITH MINOR DAMAGE CONDITIONS

6.3 SUMMARY

- This stage represents the period of the fire, after 02:00, where conditions within the wider building of Grenfell Tower could be considered as untenable.
- Egress / rescue of occupants from the tower during this stage was considerably slower than in previous stages providing an indication of increasingly challenging conditions within the building.
- Firefighter operations within this stage would likely have been confined to the lower levels due to the deteriorating conditions within the building, especially above floor 12.
- With multiple compartment fires already occurring and more igniting as the external fire continued to spread around the building, any firefighter operations or egress actions are far outside the intended strategy for the building and implied by regulatory compliance.
- Locations of fatalities are consistent with records from emergency calls and firefighter statements regarding locations where egress was compromised.
- Most fatalities occurred on the 14th to 17th and 20th to 23rd floors which corresponds to early reports of lobbies made impassable by smoke and heat.
- Flats on Level 12 and upwards almost exclusively experienced post-flashover fires. This corresponds well to observed visible structural damage.

- 3057
- 3058
- 3059
- 3060
- 3061
- 3062
- 3063
- 3064
- There is a direct correlation between number of severe fires and severely damaged lift lobbies indicating that fire doors separating individual flats from the lobbies were not sufficient for the thermal load experienced.
 - In general, the structure remains stable, however most instances of spalling and structural damage are reported in the middle floors. The reasons for this distribution are not immediately clear. While a post-fire analysis enables this conclusion, there are no realistic means by which anyone could establish during the event that the structure remained sound at this stage of the fire.

7 CONCLUSIONS

Analysis indicates that a relatively minor, localised fire, compromised the uPVC window fittings and ignited one of the flammable components of the cladding by direct flame/plume impingement. This likely occurred before 01:05, and before first responders entered Flat 16. This marked the end of the first stage of the fire. From this point forward, the “stay put” strategy was compromised and evacuation of occupants was an option to consider. Firefighters would have been operating outside of their prescribed operating procedures. The building performance implied by the design approach followed was also breached.

Fire spread up the façade was inevitable once the fire was established on the outside of the façade system. Based on similar international events, the rate of spread was not unusual. Breaching of the window assemblies of flats higher up the building was also inevitable given the comparative levels of heat flux delivered by external fires to those required to break the window assemblies or induce glazing failure. Performance of external detailing such as fire-stopping or window units had no bearing on this outcome due to fire spreading over the exterior of the façade system. Fire reached the top of the building at approximately 01:30 which marks the end of the second stage of the fire. Throughout this stage, notwithstanding the fact that tenability levels in some lift lobbies is questionable, egress or rescue is the preferred option. The structural integrity of the building is not in question.

An important conclusion that cannot be overlooked is the complexity associated with predicting the rate of spread of a fire over a system as complex as these façade systems. Current performance criteria do not give justice to the complexity of the systems and observation of past fires does not provide sufficient information. While significant non-compliances have been established, the compliance approach used to determine “adequate” fire spread needs to be revisited and should be studied in much greater detail in Phase Two. This analysis should address not only technical issues pertaining to the fire dynamics associated with these complex systems, but should also focus on the implied competence introduced by Building Regulations. It is clear that currently there is an inconsistency between the necessary competency to address such complex systems, the levels of competency interpreted as required by Building Regulations and the mechanisms that serve to enforce competency. This applies to all aspects of the design, build, approvals and maintenance processes.

One key distinction between the fire at Grenfell Tower and other fires that have seen extensive vertical fire spread was the performance of the architectural crown, in particular its propensity to support lateral flame propagation, drip molten material and drop burning debris. This architectural crown was a key component that enabled the extensive lateral spread of fire around the entirety of Grenfell Tower.

Despite having several levels of containment, smoke and heat reached the stairwell early on in the fire. A variety of potential mechanisms, most likely linked to human action, error occurring either during the fire event or during design, construction and ongoing maintenance of the building, are most likely associated with the rapid internal spread of heat and smoke within the building. This rapidly impeded egress of occupants in the region around Floor 12 and above Floor 20. While human factors are relevant, the failure of compartmentalization needs to be treated as a compliance issue. The severity of interior fires generated by external fires is most likely very similar to that of a conventional compartment fire. Thus, fire resistance requirements, if valid for a conventional compartment fire should be valid for internal fires initiated by external fires. This aspect needs to be explored in Phase Two because compliance in matters of compartmentalization should be much less complex, and thus robust improvements should be easy to implement.

3106 A combination of these mechanisms and also potentially fire door failure as a result of multiple severe
3107 compartment fires led to generalised untenable conditions throughout the Tower by approximately 01:50 –
3108 02:30. This marks the end of the third stage of the fire.

3109 Beyond this point, in the fourth stage, firefighting activities are governed by conditions in the building and are
3110 performed in an ad-hoc manner. There is considerable risk to those rescuing and being rescued, however
3111 egress remains the preferred option. Prior to widespread untenable conditions throughout the building, the
3112 structural integrity is not considered to have been compromised to an extent that put occupants and rescuers
3113 lives at risk. Only beyond the point at which general conditions in the building were untenable would the
3114 structure could be deemed at risk. Post-fire analysis indicates that this risk is generally localised and in the
3115 middle region of the building but this could have not been assessed during the event. The reasons for this are
3116 as yet undetermined. Structural assessment methods that could enable firefighters to establish the risk of
3117 structural failure appear as a potential improvement to operations and should be explored in Phase Two.

8 REFERENCES

1. Todd, C., "Legislation, Guidance and Enforcing Authorities Relevant to Fire Safety Measures at Grenfell Tower," Report for the Grenfell Public Inquiry, February 2018.
2. Nic Daeid, N., Grenfell Tower Public Inquiry, Provisional Report, GTPI/NND/2017, 12th February, 2018.
3. Bureau Veritas, Fire safety Department Report, Scene and laboratory Examinations – Flat 16 Grenfell Tower, Royal Borough of Kensington & Chelsea, LFB/17-259, 7th November, 2017.
4. Lane, B., "Grenfell Tower – fire safety investigation: The fire protection measures in place on the night of the fire, and conclusions as to the extent to which they failed to control the spread of fire and smoke; the extent to which they contributed to the speed at which the fire spread, Report, 12th of April, 2018.
5. Bisby, L., "Grenfell Tower Public Inquiry, Draft Phase 1 - Expert Report," 2nd April, 2018.
6. BS 476- 6: 1989+A1:2009, Fire tests on building materials and structures, Part 6: Method of test for fire propagation for products, BSI.
7. Torero, J.L., "The Risk Imposed by Fire to High Rise Buildings, Introduction," Fire Safety in High Rise Buildings, VDM Publishing, 1-16, 2009.
8. A. Cowlard, A. Bittern, C. Abecassis-Empis, and J. L. Torero, "Some Considerations for the Fire Safe Design of Tall Buildings," International Journal of High-Rise Buildings, March, Vol 2, No 1, 2013.
9. J.L. Torero, "Scaling-Up Fire," Proceedings of the Combustion Institute, v. 34 (1), pp. 99-124, 2013.
10. Torero, J.L., "Fire Safety Engineering: profession, occupation or trade?" International Fire Professional Magazine Vol. 1 No. 1 July 2012, Institution of Fire Engineers, UK.
11. The Building Regulations 2010, Fire Safety, Approved Document B – Volume 2, Buildings other than dwelling houses, HM Government, 2013.
12. Agarwal, G., FM Global, Research Technical Report, Evaluation of the Fire Performance of Aluminium Composite Material (ACM) Assemblies Using ANSI/FM 4880, December 2017.
13. White, N. and Delichatsios, M., "Fire Hazards of Exterior Wall Assemblies Containing Combustible Components," June 2014, Fire Protection Research Foundation, Quincy, Massachusetts, USA.
14. Morrison III, D., et al., Preliminary Fire Investigation Status Report to the Grenfell Tower Public Inquiry, Exponent, Jan 2018.
15. J.P. Hidalgo-Medina, Performance-Based Methodology for the Fire Safe Design of Insulation Materials in Energy Efficient Buildings, PhD Thesis, University of Edinburgh, 2015.
16. Ogilvie, J., "Fire Performance of ACP Façade Systems," Masters of Engineering Thesis, University of Queensland, 2017.
17. Dynamic Mechanical Analysis Data provided by Prof. Bisby, University of Edinburgh
18. C.L. Mealy et al., Fire Dynamics and Forensic Analysis of Liquid Pool Fires, Document No. 238704, May 2012, Award No. 2008-DN-BX-K168 of the U.S. Dept. of Justice
19. B.J. McCaffrey, Purely Buoyant Diffusion Flames: Some Experimental Results, National Bureau of Standards, NBSIR 79-1910
20. CIBSE Guide E, Fire Engineering, The Chartered Institution of Building Services Engineers, London, 2003.
21. Drysdale, D., "Introduction to Fire Dynamics," Third Edition, Chapter 4 – Diffusion Flames and Fire Plumes, John Wiley and Sons, 2011.
22. Alpert, R.L., Turbulent ceiling jet induced by large scale fires, Combustion, Science and Technology, 11, 197-213, 1975.
23. Drysdale, D., "Introduction to Fire Dynamics," Third Edition, Chapter 7 – Spread of Flame, John Wiley and Sons, pp. 277-315, 2011.
24. Drysdale, D., "Introduction to Fire Dynamics," Third Edition, Chapter 6 – Ignition: The Initiation of Flaming Combustion, John Wiley and Sons, 2011.

25. Hidalgo, J.P., Torero, J.L. and Welch, S., "Fire performance of charring closed-cell polymeric insulation materials: Polyisocyanurate and phenolic foam," *Fire and Materials*, (in press) 2018.
26. SFPE Handbook of Fire Protection Engineering, 3rd Edition, SFPE-NFPA, 2002.
27. BS 8414-2:2015+A1:2007, Fire performance of external cladding systems. Test method for non-loadbearing external cladding systems fixed to and supported by a structural steel frame, BS1, 2015.
28. Quintiere, J.G., *Principles of Fire Behavior*, 1st Edition, Delmar Publishers, 1997
29. Harada, K., Enomoto, A., Uede, K. and Wakamatsu, T., "An Experimental Study on Glass Cracking and Fallout by Radiant Heat Exposure," *Fire Safety Science*, v.6, pp.1063-1074, 2000.
30. Kuang-Chung, T., et al., "Upward Flame Spread: Heat Transfer to the Unburned Surface", *Fire Safety Science*, pp. 117-128, 2002.
31. Lee, Y.P., Delichatsios, M.A., and Silcock, G.W.H., "Heat Flux Distribution and Flame Shapes on the Inert Façade", *Fire Safety Science*, pp. 193-204, 2008.
32. Quintiere, J., Harkleroad, M., and Hasemi, Y., "Wall Flames and Implications for Upward Flame Spread," *Combustion, Science and Technology*, Vol. 48, pp. 191-222, 1986.
33. Mowrer, F.W., and Williamson, R.B., "Flame Spread Evaluation for Thin Interior Finish Materials," in *Fire Safety Science - Proceedings of the Third International Symposium*, eds. G. Cox and B. Langford, pp. 689-698, Elsevier, London, 1991
34. Drysdale, D., "Introduction to Fire Dynamics," Third Edition, Chapter 9 – Pre-flashover Compartment Fire, John Wiley and Sons, pp. 349-386, 2011.
35. Drysdale, D., "Introduction to Fire Dynamics," Third Edition, Chapter 10 – Post-Flashover Compartment Fire, John Wiley and Sons, 2011.
36. Crowder, D. and Holland, C., BRE Global, Briefing Note on Doors and Public Safety, Reference: P109378-1001, Issue 1, February 14th, 2018.
37. Thomas, P.H., and Heselden, A.J.M., Fully developed fires in single compartments, - FRN 923, Borehamwood, 1972.
38. Kawagoe, K., Sekine, T., Estimation of fire temperature-time curve in rooms, 1963.
39. BS EN 1991-1-2:2002, Eurocode 1: Actions on structures – Part 1-2: General actions – Actions on structures exposed to fire.
40. Drysdale D.D., Thermochemistry, Section 1, Chapter 5, SFPE Handbook, 3rd Edition, SFPE-NFPA, 2002.
41. CFRA Fire and Rescue Authorities Operational Guidance, GRA 3.2 Fighting fires – In high rise buildings, Dept. CLG, Feb 2014.
42. Tamura, G.T., Smoke Movement and Control in High Rise Buildings, National Fire Protection Association, 1994.
43. Simpson, S., Grenfell Tower: Existing Building Overview, DeconstructUK.com, 12th November 2017.
44. Buchanan, A.H., *Structural Design for Fire Safety*, John Wiley and Sons Ltd, 2002.
45. Drysdale, D., "Introduction to Fire Dynamics," Third Edition, Chapter 1 – Fire Science and Combustion, John Wiley and Sons, 2011
46. BS EN 1992-1-2: 2004, Eurocode 2: Design of concrete structures – Part 1-2: General rules – Structural fire design.
47. H.W. Emmons, The Numerical Solution of Heat Conduction Problems, *Transactions of the American Society of Mechanical Engineers (ASME)*, 65 (6), 1943, p607-615.
48. G.M. Dusinberre, *Heat Transfer Calculations by Finite Differences*, International Textbook Company: Pennsylvania, US, 1961, 293 pp.
49. C.H. Maluk, Development and Application of a Novel Test Method for Studying the Fire Behaviour of CFRP Prestressed Concrete Structural Elements, PhD Thesis, University of Edinburgh, 2014.

APPENDIX A. SMOKE FILLING MODEL

The description of the fire growth in the early stages of the fire depends on the surface area of combustible materials burning, as well as on the type of fuels burning. In most cases it is very difficult to establish precisely what is burning, the relevant properties of the materials and also the area burning. A simple and common way of characterizing a wide range of growing fires is the “ αt^2 ” fire [20]. The value of “ α ” represents all the properties of the burning materials while the “ t^2 ” the growth of the area in time (t is time in seconds). Many tests have been done in the past for various materials and data sets are available that serve to characterize the corresponding value of “ α ” for numerous combustible materials. These classify fires in four categories: slow, medium, fast and ultra-fast fire growth. The value of “ α [kW/s²]” covers the range of $\alpha=0.0029$ for a slow fire to $\alpha=0.1876$ for an ultra-fast fire. To represent a broad spectrum of fire growth behaviour the whole range of fire growth rates will be used here. This is necessary given the lack of clarity regarding the exact point of origin and thus type, orientation and position of the fuel exposed. The range covers all possible fires according to the available literature data. The range is not established to attempt to define the actual rate of growth of the fire, but to cover all possible conditions.

The model, described below, solves a simple set of equations over sequential, small time, increments to describe the amount of smoke produced by a fire and the subsequent contribution that it makes to the hot-layer of smoke that builds beneath the compartment ceiling, and gradually descends towards the floor. Where terms in these expressions span across time-steps, superscripts t and $t+1$ have been used to differentiate between terms that refer to the previous and new time-step respectively. Where no guidance is given, all terms refer to the same time-step.

The size of the fire, \dot{Q} (kW) at any point in time, t (s), post-ignition, is characterised as:

$$\dot{Q} = \alpha t^2$$

EQUATION 4

It is only the convective portion of this total energy release that contributes to the fire plume, and this portion, \dot{Q}_c (kW), is defined as:

$$\dot{Q}_c = \frac{\dot{Q}}{1.5}$$

EQUATION 5

As the plume rises due to buoyancy created by this heat, \dot{Q}_c , air is entrained into the plume causing it to increase in mass the higher it rises. The mass flow rate of smoke in the plume, \dot{M}_a (kg/s), as a function of the height above the base of the fire, z (m), is given as:

$$\dot{M}_a = E \left(\frac{g \cdot \rho_a^2}{c_p \cdot T_a} \right)^{\frac{1}{3}} \cdot \dot{Q}_c^{\frac{1}{3}} \cdot z^{\frac{5}{3}}$$

EQUATION 6

Where E is a dimensionless constant (0.21), g is the acceleration due to gravity (9.81 m/s²), ρ_a is the density of air (1.2 kg/m³), c_p is the specific heat capacity of air (1.0 J/kg.K), and T_a is the temperature of the ambient air (288 K).

3153 This entrained air is orders of magnitude larger than the other components of the smoke, therefore the mass
 3154 flow of air is assumed to be equivalent to the mass flow of smoke in the plume, \dot{M}_s (kg/s), therefore:

$$3155 \quad \dot{M}_a \approx \dot{M}_s$$

3156 EQUATION 7

3157 It is this mass flow that creates and subsequently continually feeds the smoke layer. Thus, it is necessary to
 3158 determine the temperature of the smoke plume, T_s (K), to subsequently establish the temperature of the hot
 3159 upper layer, T_u (K). The smoke plume is given as:

$$3160 \quad T_s = T_a + \frac{\dot{Q}_c}{\dot{M}_s \cdot c_p}$$

3161 EQUATION 8

3162 Having established the characteristics (mass and temperature) of the smoke entering the upper layer, the
 3163 mass of the upper layer, m_u (kg), can be established at each time-step as:

$$3164 \quad m_u^{t+1} = m_u^t + \dot{M}_s^{t+1} \cdot \Delta t$$

3165 EQUATION 9

3166 Where Δt is the length of the timestep (s). This mass can be equated to a height of the smoke layer, H (m),
 3167 using the temperature, T_u (K), and subsequently density, ρ_u (kg/m³), of the upper layer. The temperature of
 3168 the upper layer, T_u (K), is established as:

$$3169 \quad T_u^{t+1} = \frac{m_u^t T_u^t + \dot{M}_s^{t+1} T_s^{t+1} \Delta t}{m_u^t + \dot{M}_s^{t+1} \Delta t}$$

3170 EQUATION 10

3171 The density of the upper layer, ρ_u (kg/m³), is established as:

$$3172 \quad \rho_u = \rho_\infty \left(\frac{T_a}{T_u} \right)$$

3173 EQUATION 11

3174 These parameters are then equated to the height of the smoke layer, H (m), as:

$$3175 \quad H = \frac{m_u}{A \cdot \rho_u}$$

3176 EQUATION 12

3177 Where A (m) is the area of the footprint of the compartment. Combined, these expressions can be used to
 3178 depict the evolution of the smoke layer height and temperature.

APPENDIX B. Verification of Bounding Fire Sizes

Zone modelling of the kitchen fire in Flat 16 has been performed using the Consolidated Model of Smoke and Heat Transport (CFAST)²⁶ tool developed at the National Institute of Standards and Technology, US. This tool is used to assess temperatures and HRRs at the point in time when the smoke layer interface reaches its lowest point.

CFAST Model Scenarios

Two model variations of the Flat 16 fire scenario have been constructed. Scenario 1 represents the assumed ventilation conditions during the kitchen fire event based on the available evidence. The kitchen door is closed and the kitchen window is only partially open. An example of this scenario is shown in Figure 80. The purpose of this model is to provide verification of the range of compartment temperature and HRR estimated by the analytical approach described in the main body of this report.

Scenario 2 takes advantage of the extra functionality of the model to explore the potential conditions that could result from different ventilation configurations, namely if the kitchen door was open or closed for the duration of the fire, to try to provide confirmation of this potential variable. Thermal imaging camera footage [MET00005810-17] show the door and window to Bedroom 1 open as the firefighters enter and search the flat for the first time. The Scenario 2 model replicated this.

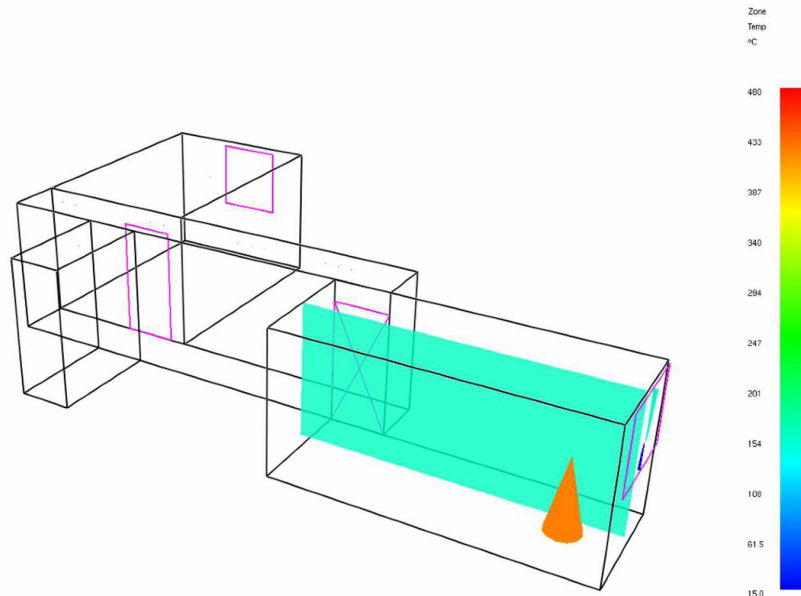


FIGURE 80: SCENARIO 1: KITCHEN FIRE SCENARIO WITH VENTILATION CONDITIONS BASED ON OBSERVED EVIDENCE. THE KITCHEN DOOR IS CLOSED, AND KITCHEN WINDOW IS PARTIALLY OPEN.

²⁶<https://www.nist.gov/el/fire-research-division-73300/product-services/consolidated-fire-and-smoke-transport-model-cfast>

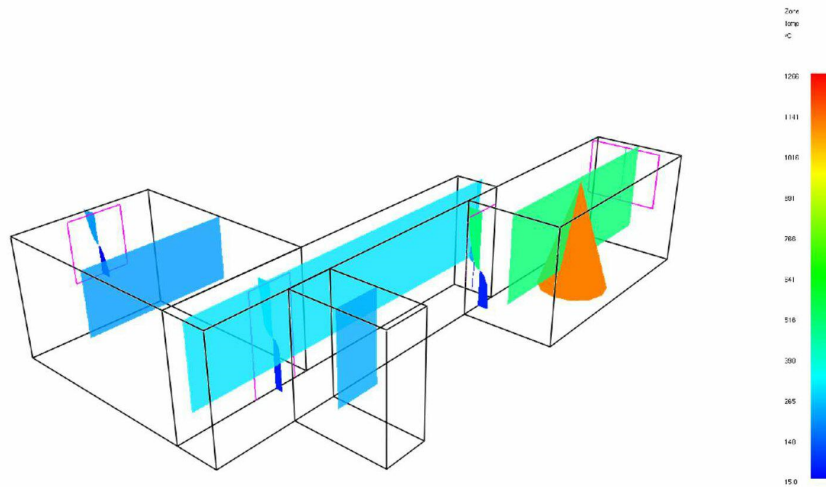


FIGURE 81: SCENARIO 2: KITCHEN FIRE SCENARIO WITH WINDOW PARTIALLY OPEN AND KITCHEN DOOR FULLY OPEN. THE DOOR FROM THE CORRIDOR TO BEDROOM 1 AND WINDOW IN BEDROOM 1 ARE ALSO OPEN AS OBSERVED IN THERMAL IMAGING CAMERA FOOTAGE [MET00005810-17].

Characteristic Fire Scenarios

Four characteristic fire growth rates are simulated to establish bounding values for the compartment temperature and HRR at the point when the kitchen compartment has filled with smoke. Growth rates represent the range explored in the main body of the report i.e. slow, medium, fast and ultra-fast. The HRR is allowed to grow and the value at the time corresponding to the smoke layer interface reaching the compartment floor is recorded. The model also provides some measure of physical cap on the magnitude of the HRR and the model is allowed to run in order to see what this value is. The other results recorded are the time at which the smoke layer interface reaches the floor and the temperature of the smoke layer at this time. Results are presented in Table 7 and discussed below.

Results

Results from Scenario 1 modelling correlate well with the results from the analytical model described in the main body of the report. The results show the range of time for the smoke layer to descend as 50 – 200s (40 – 140s in empirical model), the upper layer temperature range at this point as 125 – 250°C (100 – 220°C in empirical model), the range of HRR at this time as 110 – 360kW (60 – 300kW in empirical model) and the limiting peak HRR imposed by the model as ~360kW.

Results from Scenario 2 demonstrate that the extra ventilation provided by the open door would likely lead to a flashover scenario. The smoke layer takes longer to reach its lowest point due to the extra leakage to the rest of Flat 16 (115 – 850s). The upper layer temperature at the point at which the smoke layer interface reaches its lowest point is in the range of 750 – 900°C, temperatures beyond the 500 – 600°C range associated to flashover conditions [21]. The corresponding peak HRR which is the limiting value imposed by the model is of the order of 1.5MW.

| Scenario | Growth Rate | Spread Rate [mm/s] | Ventilation | Time for Smoke Layer to Reach Floor [s] | Corresponding Temperature of Hot Layer [°C] | Corresponding HRR [kW] | Peak HRR [kW] |
|----------|-------------|-----------------------|--|--|--|------------------------------|------------------|
| 1 | Slow | 1.2 | Kitchen Window 10% | 200 | 125 | 110 | 350 |
| 1 | Medium | 4 | Kitchen Window 10% | 125 | 160 | 160 | 355 |
| 1 | Fast | 6.7 | Kitchen Window 10% | 75 | 175 | 250 | 360 |
| 1 | Ultra-Fast | 9.5 | Kitchen Window 10% | 50 | 250 | 360 | 360 |
| 2 | Slow | 1.2 | Kitchen Window 10%, Kitchen Door 95% | 850 | 900 | 1550 | 1550 |
| 2 | Medium | 4 | Kitchen Window 10%, Kitchen Door 95% | 500 | 875 | 1550 | 1550 |
| 2 | Fast | 6.7 | Kitchen Window 10%, Kitchen Door 95% | 220 | 850 | 1550 | 1550 |
| 2 | Ultra-Fast | 9.5 | Kitchen Window 10%, Kitchen Door 95% | 115 | 750 | 1550 | 1550 |

3228

3229 Table 7: Results from the 8 CFAST model configurations run

3230

APPENDIX C. ESTIMATION OF FIRE BASE AREA

From the perspective of design, fires growth rates (α values) are grouped into categories according to how quickly a fire is expected to grow in a particular occupancy, based on the typical materials found in that occupancy. For example, a fire in an occupancy with strict controls on flammable materials would be expected to experience a slow fire growth rate.

These values are essentially representative of material properties, as will be demonstrated subsequently. The slow fire represents materials that would typically propagate fire slowly, and vice-versa for ultrafast.

Given the unknowns associated to the exact fire origin in the case of Grenfell Tower, it is difficult to isolate a representative alpha, hence the inability to bound the value of alpha used in the previous section of this analysis more precisely than the two extremes used.

As stated above, alpha, α (kW/s^2), is representative of the typical materials expected to be present in the occupancy under consideration, and thus can be broken down into a number of parameters that are time independent, material properties. α is related to the HRR, \dot{Q} (kW), according to the following relationship:

$$\dot{Q} = \alpha t^2 = \dot{m}_f \Delta H_c$$

EQUATION 13

Where t (s) is the time from the ignition of the fire, \dot{m}_f (kg/s), is the mass loss rate of the burning fuel i.e. it's rate of decomposition from solid to gaseous fuel, and ΔH_c (J/kg), is the heat of combustion of the fuel i.e. the energy produced by burning each kg of fuel that is gasified.

The mass loss rate can be made time independent by a simple augmentation of the equation where multiplying by the area of the fire, A (m^2) at any time t , it can be replaced as a characteristic mass loss rate per unit area, \dot{m}_f'' (kg/s.m^2), as follows:

$$\dot{m}_f \Delta H_c = A \dot{m}_f'' \Delta H_c$$

EQUATION 14

The αt^2 correlation represents a radially growing fire, therefore the area, A , at any point is a circle, and thus can be expressed as:

$$A = \pi r^2$$

EQUATION 15

Where r (m) is the radius of the circle and in real terms, the distance travelled by the fire in any direction from the point of origin at any time t (s). This enables the expression of the characteristic lateral spread rate of the fire, V_s (m/s) as:

$$V_s = \frac{r}{t}$$

EQUATION 16

Rearranging as:

3265
$$r^2 = V_s^2 t^2$$

3266 EQUATION 17

3267 And substituting EQUATION 17 into EQUATION 15, and the result into EQUATION 14, the result is as follows:

3268
$$\alpha t^2 = (\pi V_s^2 \dot{m}_f'' \Delta H_c) t^2$$

3269 EQUATION 18

3270 Thus α is expressed as a function of a mathematical constant and time independent, characteristic material
3271 properties.

3272 According to the report by Prof. Bisby [5], most of the combustible elements in the area of the kitchen
3273 identified are polymers, therefore characteristic polymer values are assumed and taken from Drysdale [45] as:

3274 • $\dot{m}_f'' = 0.01 - 0.014 \text{ kg/s.m}^2$

3275 • $\Delta H_c = 40 - 46 \text{ MJ/kg}$

3276 Other bounding values are:

3277 • $\alpha = 0.0029 - 0.1876 \text{ kW/s}^2$

3278 • $t_{\text{growth}} = 40 \text{ s (ultrafast) and } 138 \text{ s (slow)}$

3279 • $\pi = 3.14$

3280 Using these parameters, it is possible to establish a range of values for the spread rate of the fire, V_s (m/s) as:

3281
$$V_s = \left(\frac{\alpha}{\pi \dot{m}_f'' \Delta H_c} \right)^{\frac{1}{2}}$$

3282 EQUATION 19

3283 And thus the area of the fire as:

3284
$$A = \pi (V_s t_{\text{growth}})^2$$

3285 EQUATION 20

3286 The heat release rate, \dot{Q} (kW), can then be verified against the earlier results from **Error! Reference source**
3287 **not found.** using EQUATION 14. The results of this stage of the analysis are presented in **Error! Reference source**
3288 **not found.** below.

| α [kW/m ²] | \dot{m}_f'' [kg/s.m ²] | ΔH_c [MJ/kg] | V_s [mm/s] | A [m ²] | r [m] | \dot{Q} [kW] |
|----------------------------------|---|-------------------------|-----------------|------------------------|----------|-------------------|
| 0.0029 (S) | 0.01 | 40 | 1.5 | 0.14 | 0.2 | 55 |
| 0.0029 (S) | 0.014 | 46 | 1.2 | 0.085 | 0.17 | 55 |
| 0.1876 (UF) | 0.01 | 40 | 12.2 | 0.75 | 0.5 | 300 |
| 0.1876 (UF) | 0.014 | 46 | 9.5 | 0.46 | 0.4 | 300 |

3289

3290 TABLE 8: RESULTS OF THE ASSESSMENT TO BOUND THE FIRE AREA BY MEANS OF CHARACTERISTIC MATERIAL PROPERTIES.

APPENDIX D. ESTIMATION OF THE uPVC TEMPERATURE

A simple heat storage analysis is conducted to approximate the change in temperature of the uPVC as a result of exposure to the hot-layer gases, and thus establish if any thermal degradation of the material is possible within the timeframe provided by the evidence in section 0. The analysis equates the energy stored in the uPVC (E_{STO} , J) to the energy provided by the fire environment (E_{IN} , J) as:

$$E_{IN} = E_{STO}$$

EQUATION 21

The calculation is deliberately kept to a crude approximation, thus no losses have been assumed, as the intention is simply to provide a bounding heating time. Each term can be expanded as:

$$h_T(T_g - T_s)A = \rho \cdot c_p \cdot V \cdot \frac{\Delta T_s}{\Delta t}$$

EQUATION 22

Where h_T is the total heat transfer coefficient (25 W/m².K), T_g is the gas phase (hot layer) temperature (K), T_s is the solid (uPVC) temperature (K), A is the exposed surface area (m²), ρ is the density of the solid (1390 kg/m³), c_p is the specific heat capacity of the solid (1170 J/kg.K), V is the volume of the solid (m³), and ΔT_s is the change in temperature of the solid, and Δt is the time-step (s). This expression can be rearranged in terms of ΔT_s as:

$$\Delta T_s = \frac{h_T(T_g - T_s)\Delta t}{\rho \cdot c_p \cdot \delta}$$

EQUATION 23

Where δ is the thickness of the uPVC (9.5mm) derived from the ratio of volume (V) and surface area (A).

APPENDIX E. STEP BY STEP LATERAL FLAME SPREAD

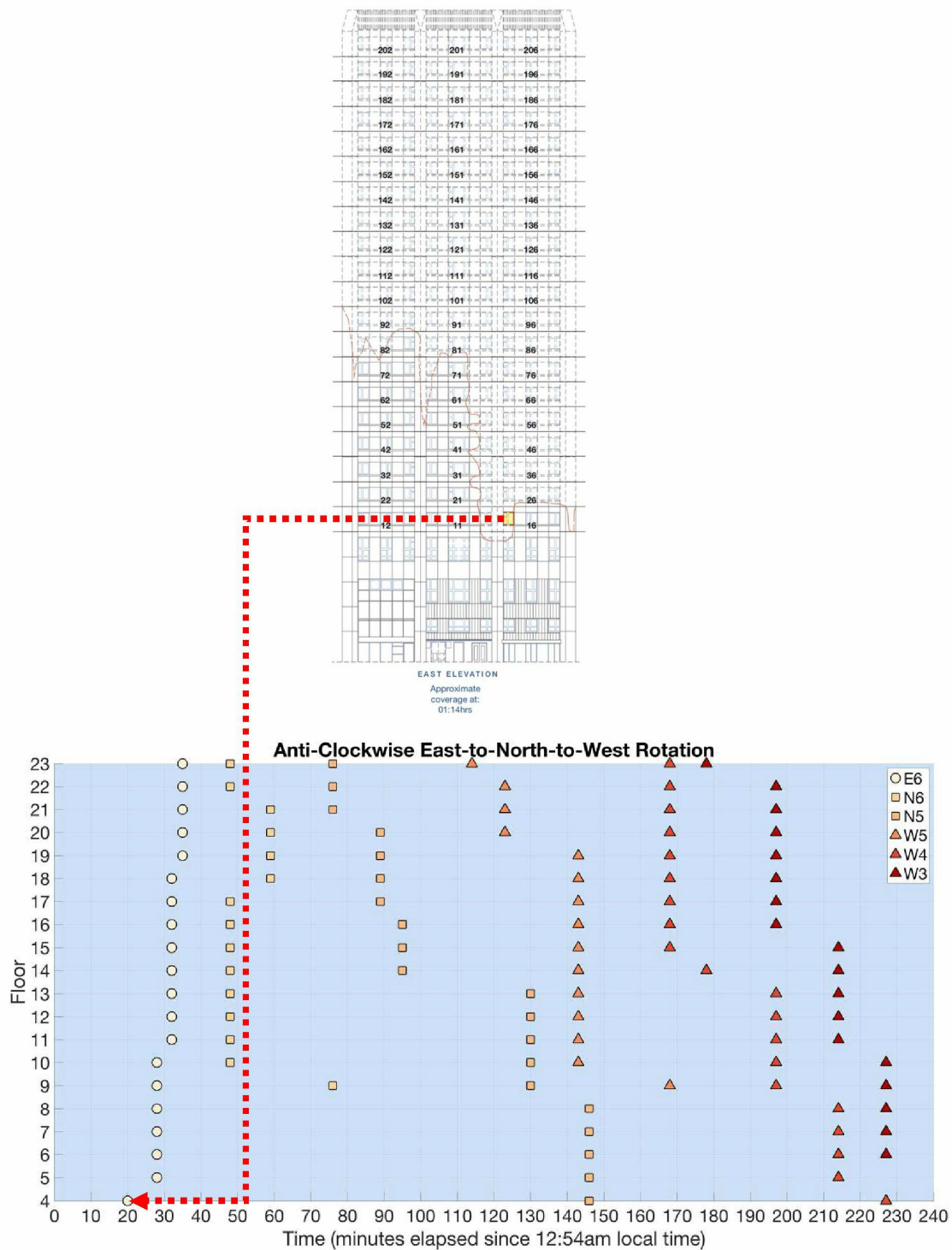


FIGURE 82: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 01:14 AM ON THE EAST ELEVATION TOWER PLAN VIEW.

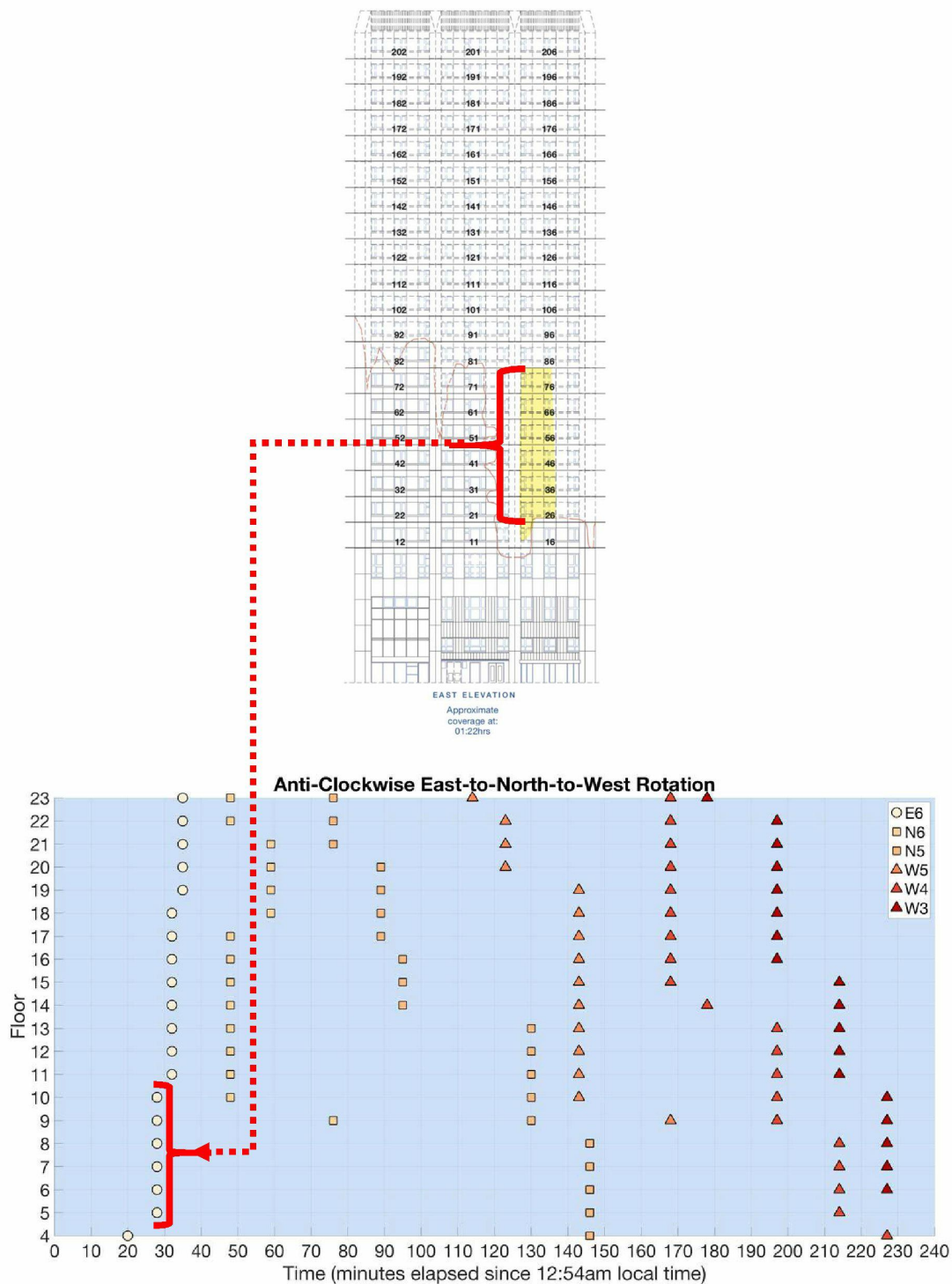


FIGURE 83: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 01:22 AM ON THE EAST ELEVATION TOWER PLAN VIEW.

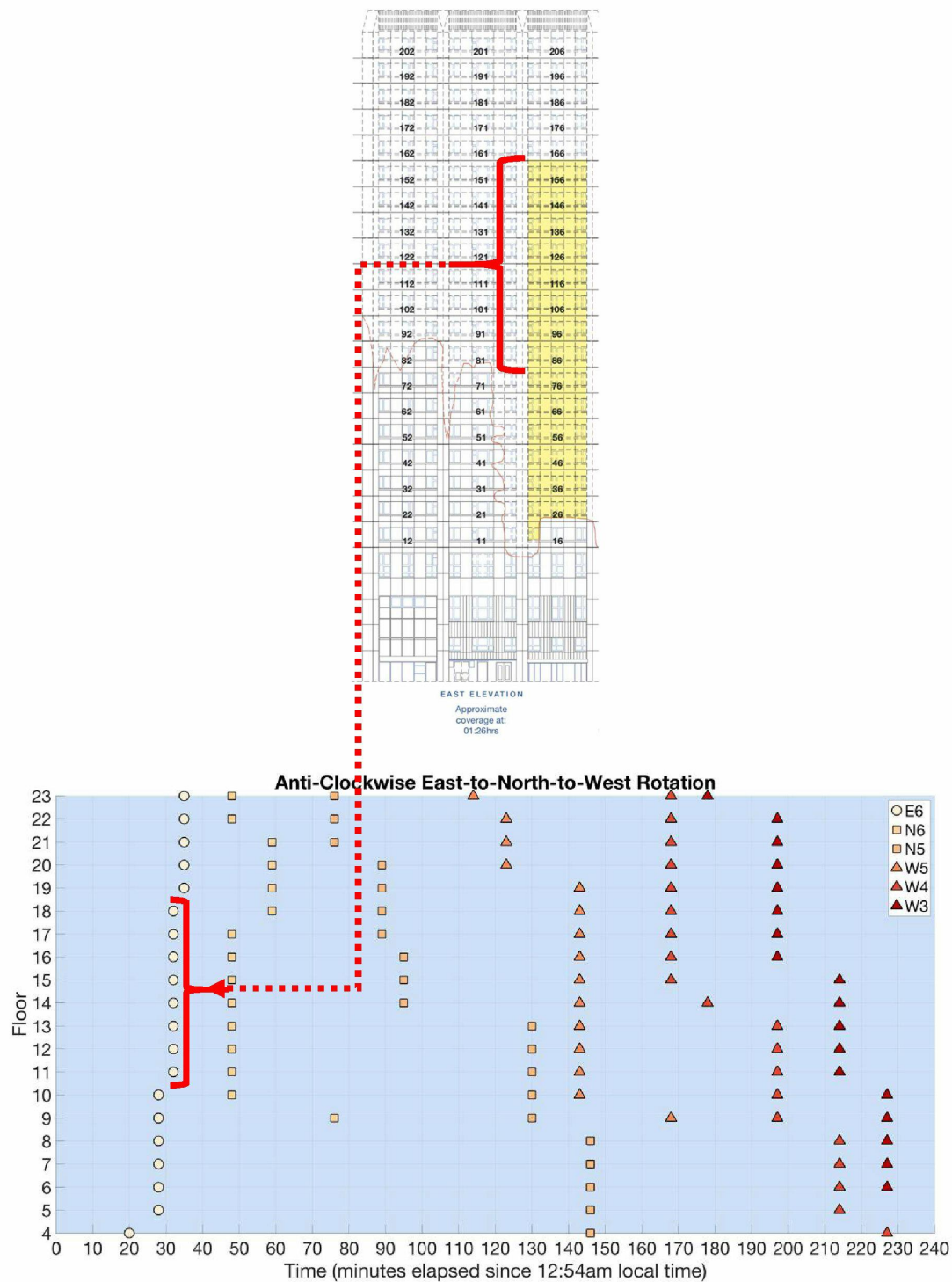


FIGURE 84: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 01:26 AM ON THE EAST ELEVATION TOWER PLAN VIEW.

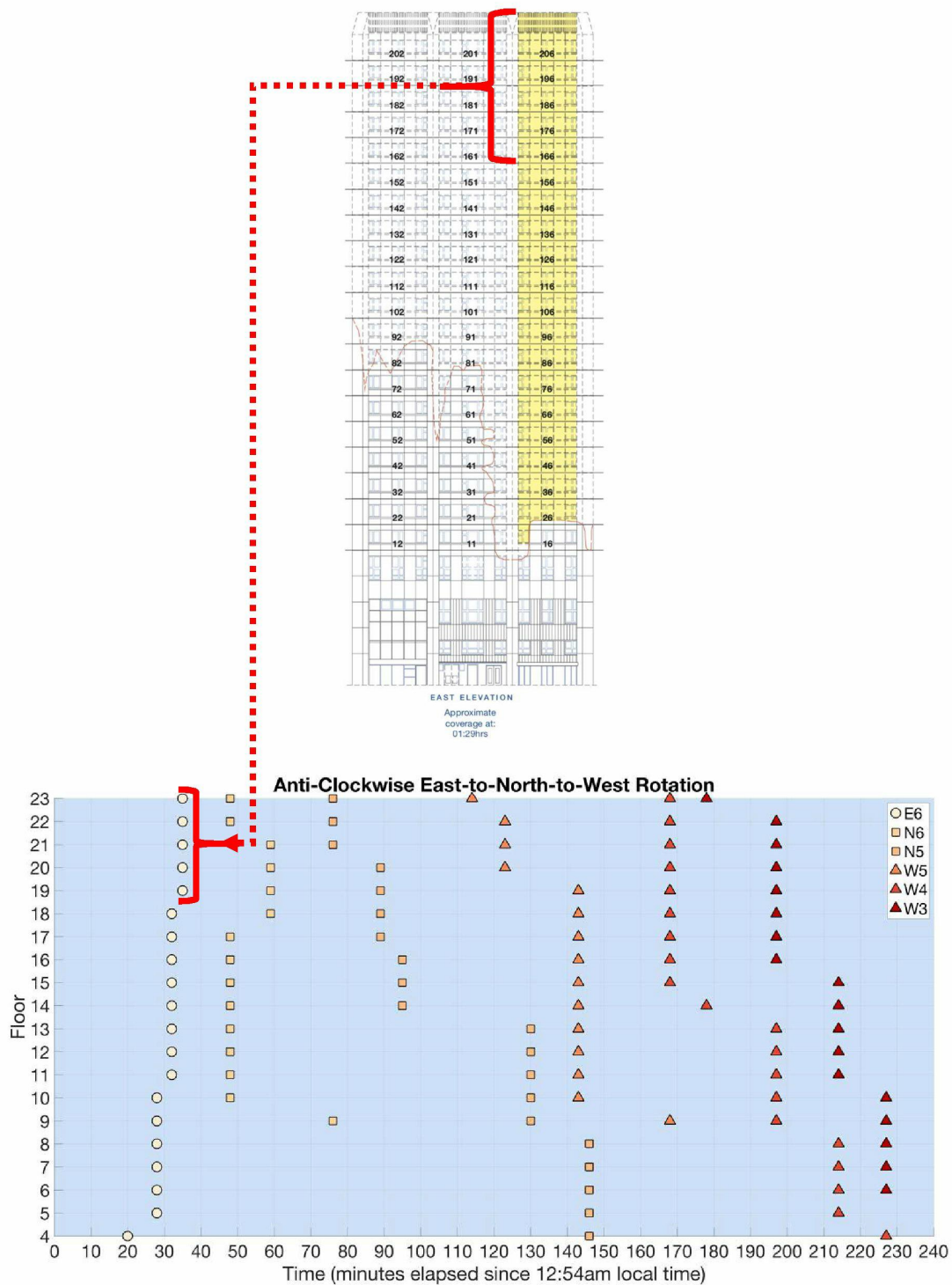


FIGURE 85: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 01:29 AM ON THE EAST ELEVATION TOWER PLAN VIEW.

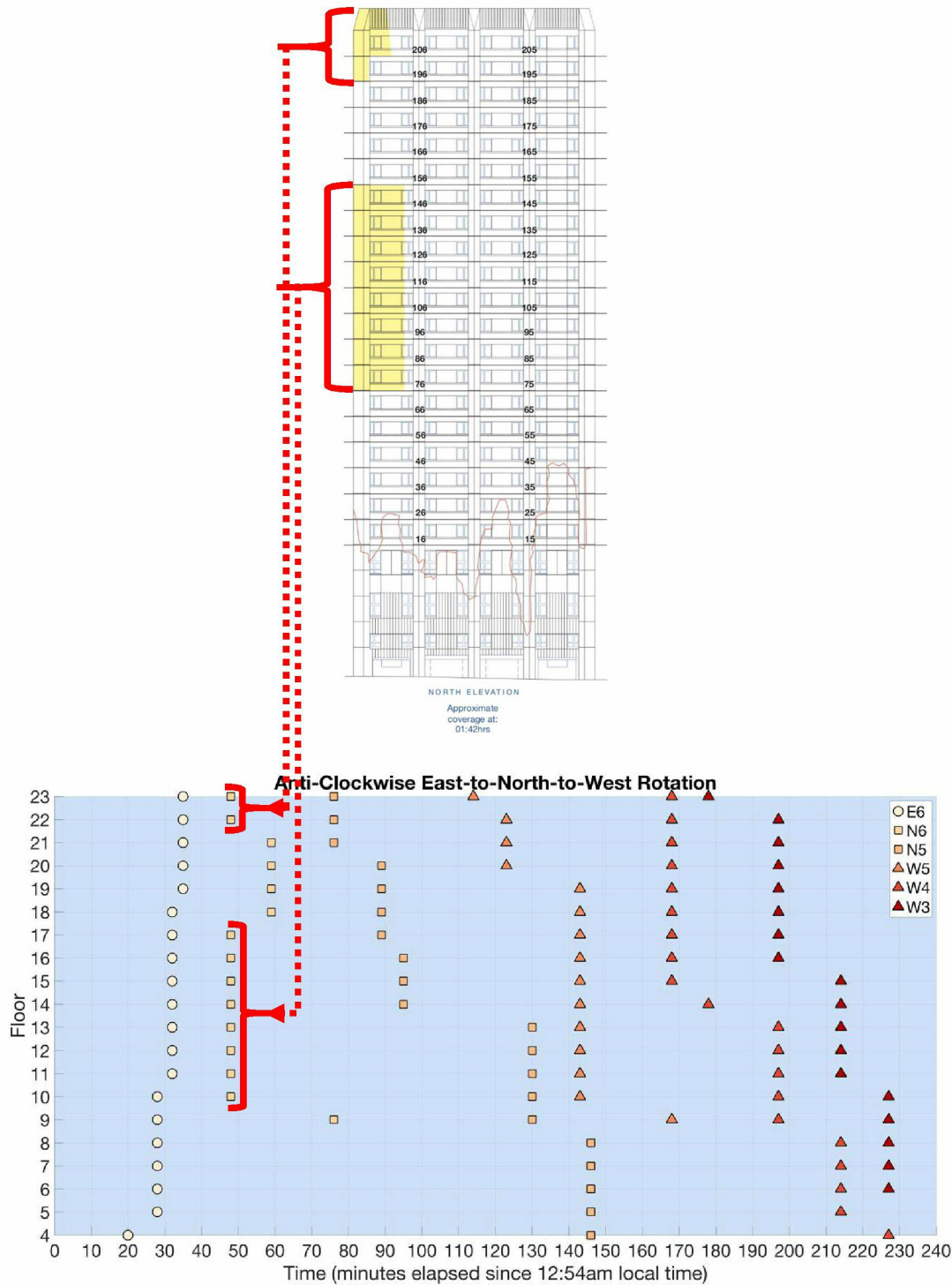


FIGURE 86: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROWS INDICATE THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 01:42 AM ON THE NORTH ELEVATION TOWER PLAN VIEW.



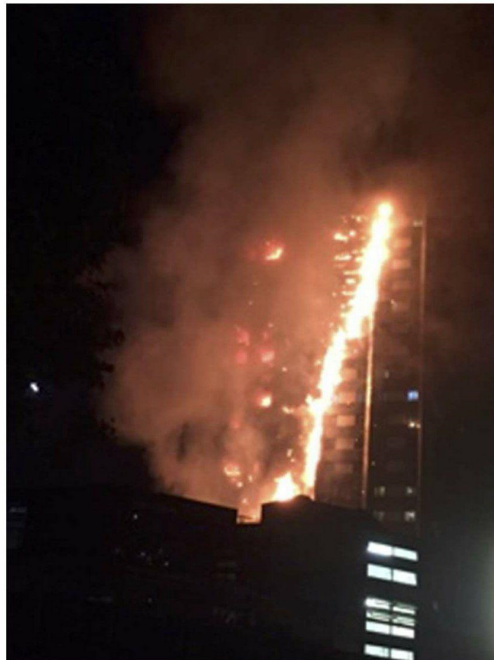
(a)



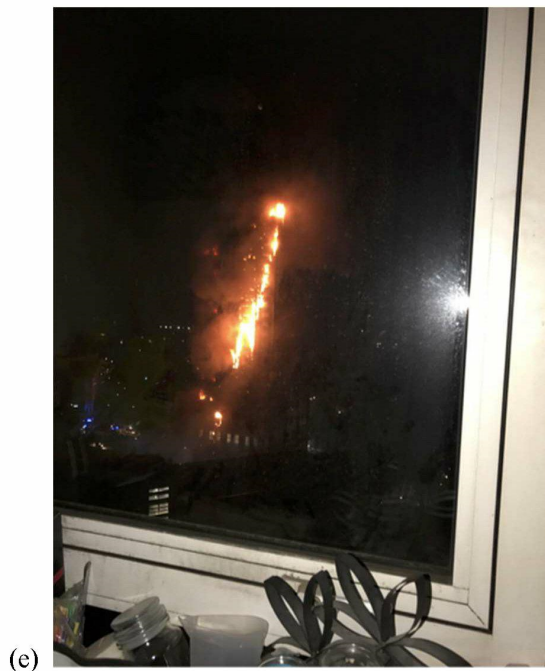
(b)



(c)



(d)



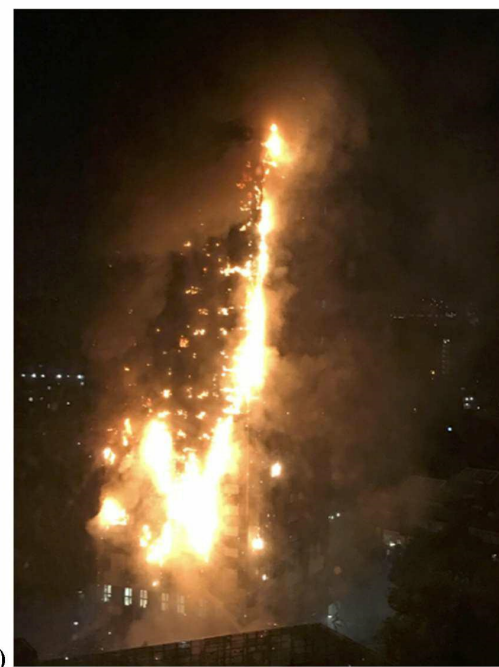
(e)



(f)



(g)



(h)

FIGURE 87: ORIGINAL PUBLIC FOOTAGE OF LATERAL AND VERTICAL (DOWNWARD) FLAME SPREAD ON THE NORTH FACADE OF GRENFELL TOWER AT (A) 01:42 AM; (B) 01:53 AM; (C) 02:23 AM; (D) 02:32 AM; (E) 02:49 AM; (F) 02:55 AM; (G) 03:04 AM; AND (H) 03:07 AM RESPECTIVELY. PHOTOS WERE SOURCED FROM MET00008024, PAGE 36.

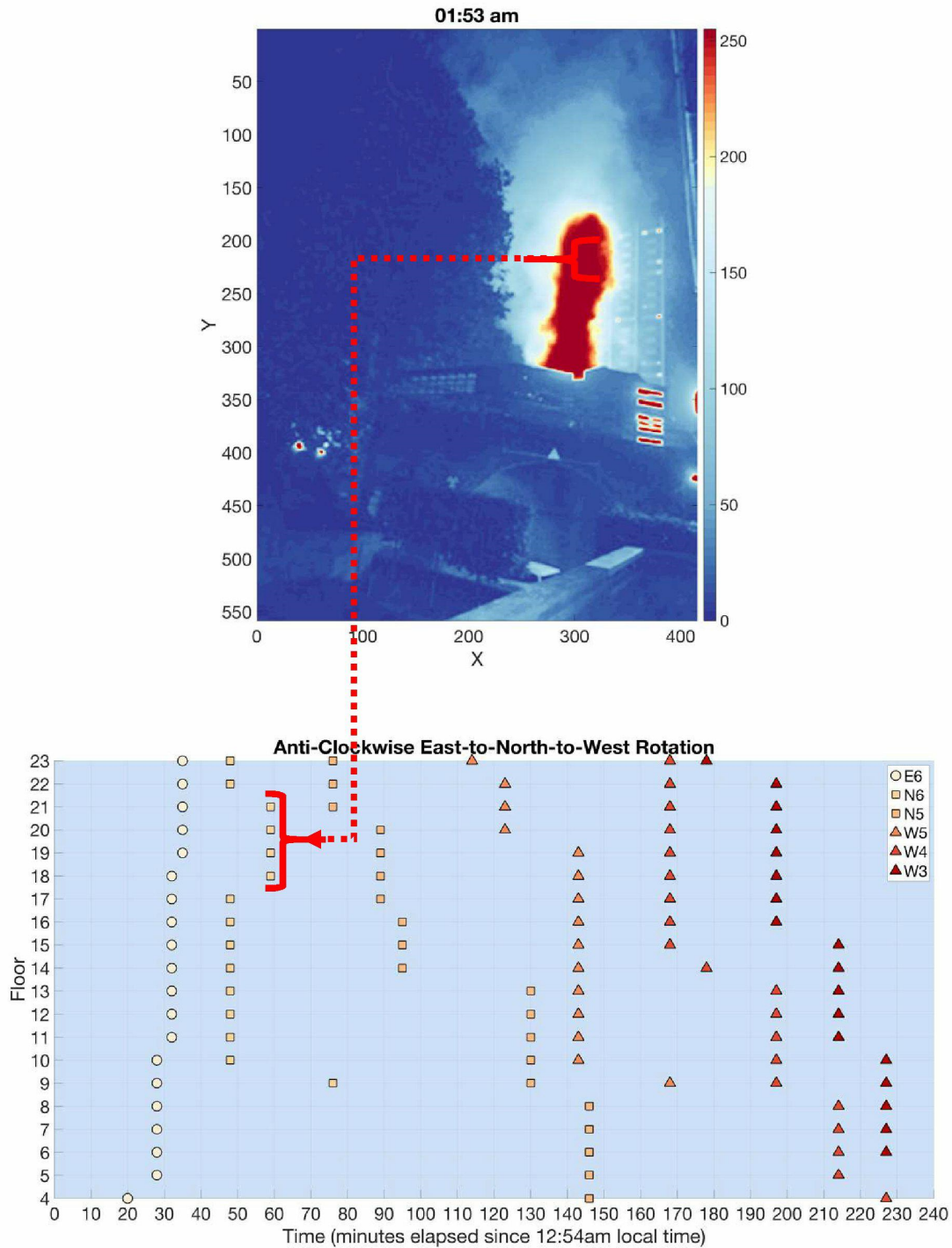


FIGURE 88: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 01:53 AM ON THE NORTH ELEVATION PROCESSED IMAGE (FIGURE 5b).

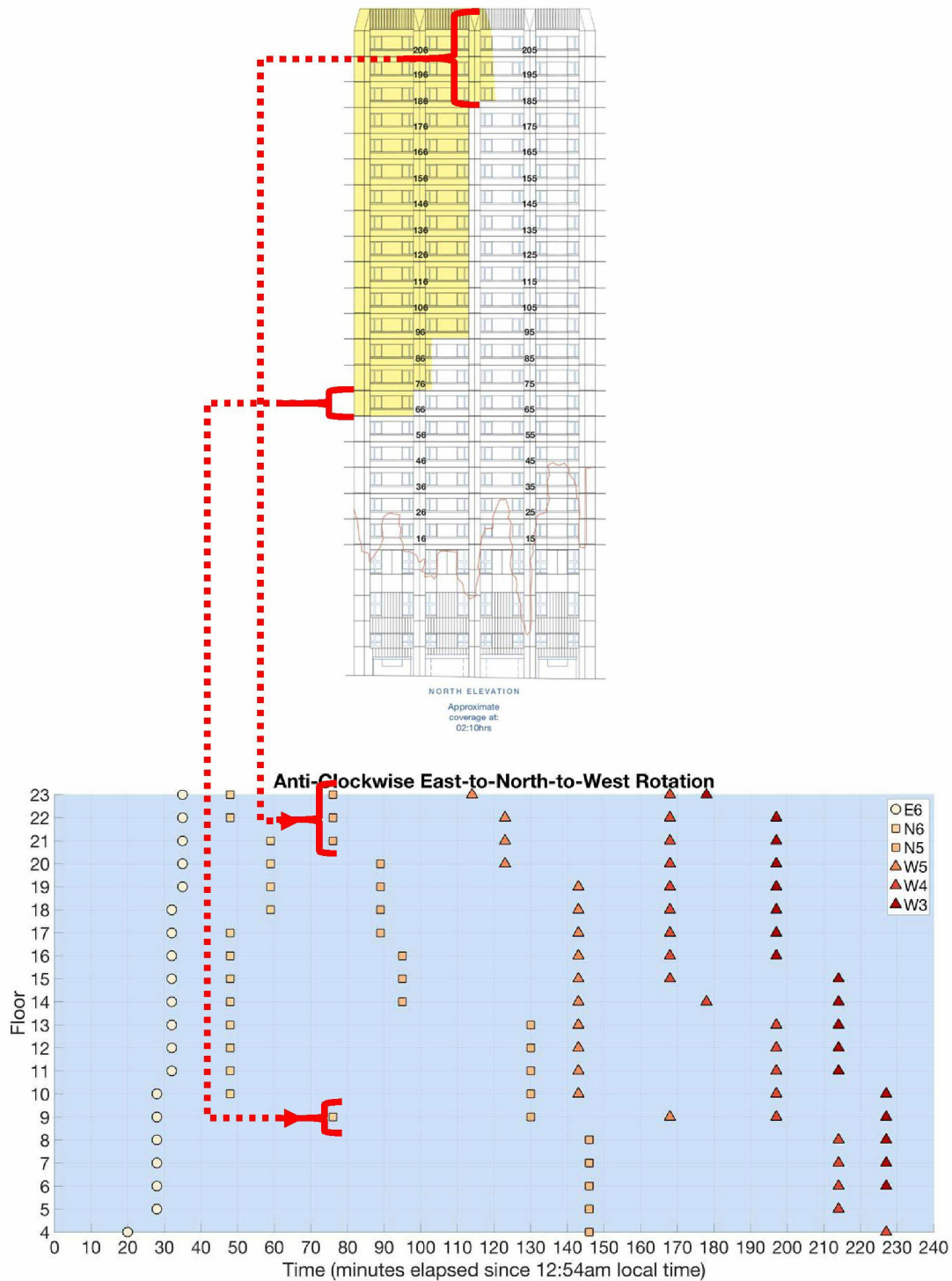


FIGURE 89: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROWS INDICATE THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 02:10 AM ON THE NORTH ELEVATION TOWER PLAN VIEW.

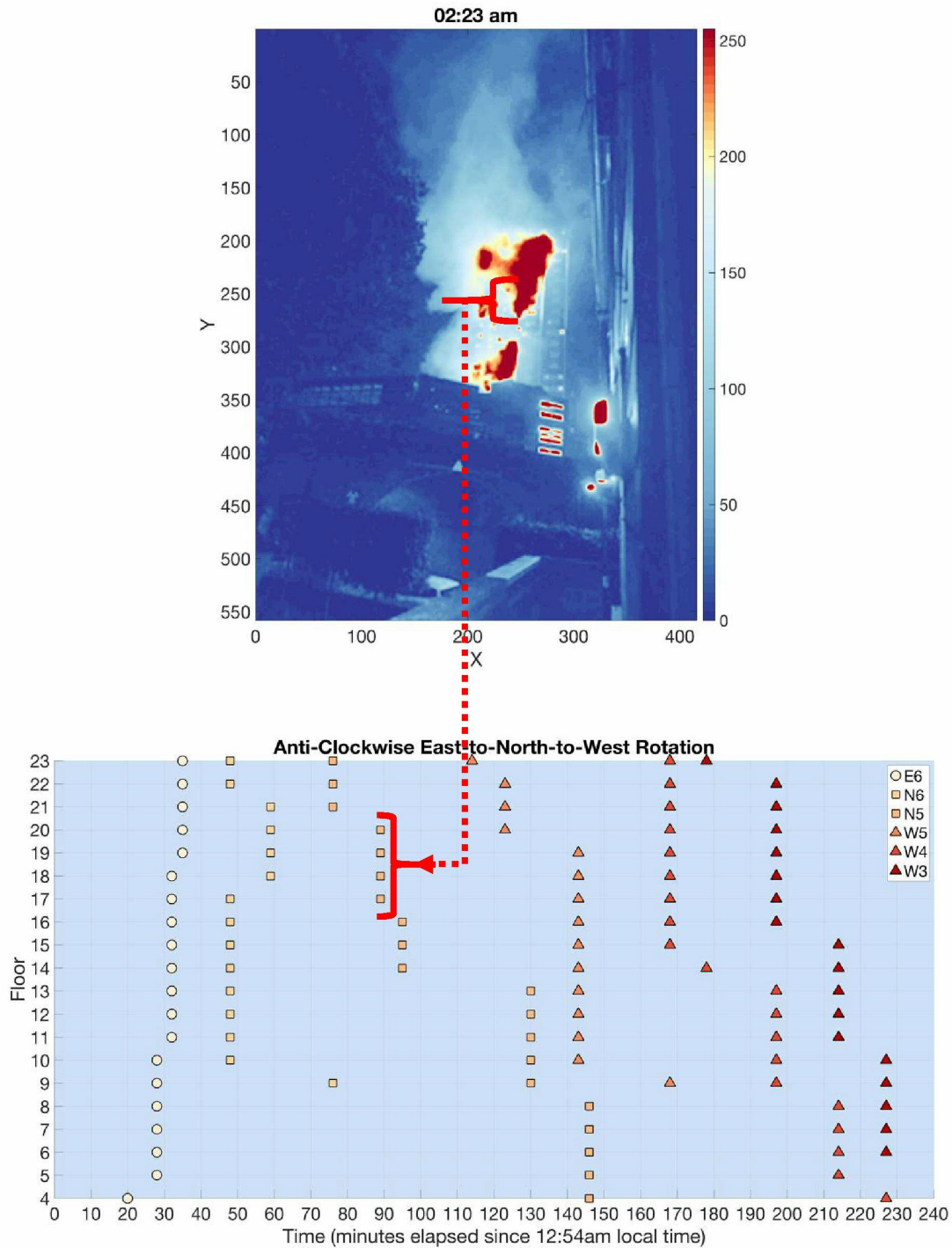


FIGURE 90: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 02:23 AM ON THE NORTH ELEVATION PROCESSED IMAGE (FIGURE 5c).

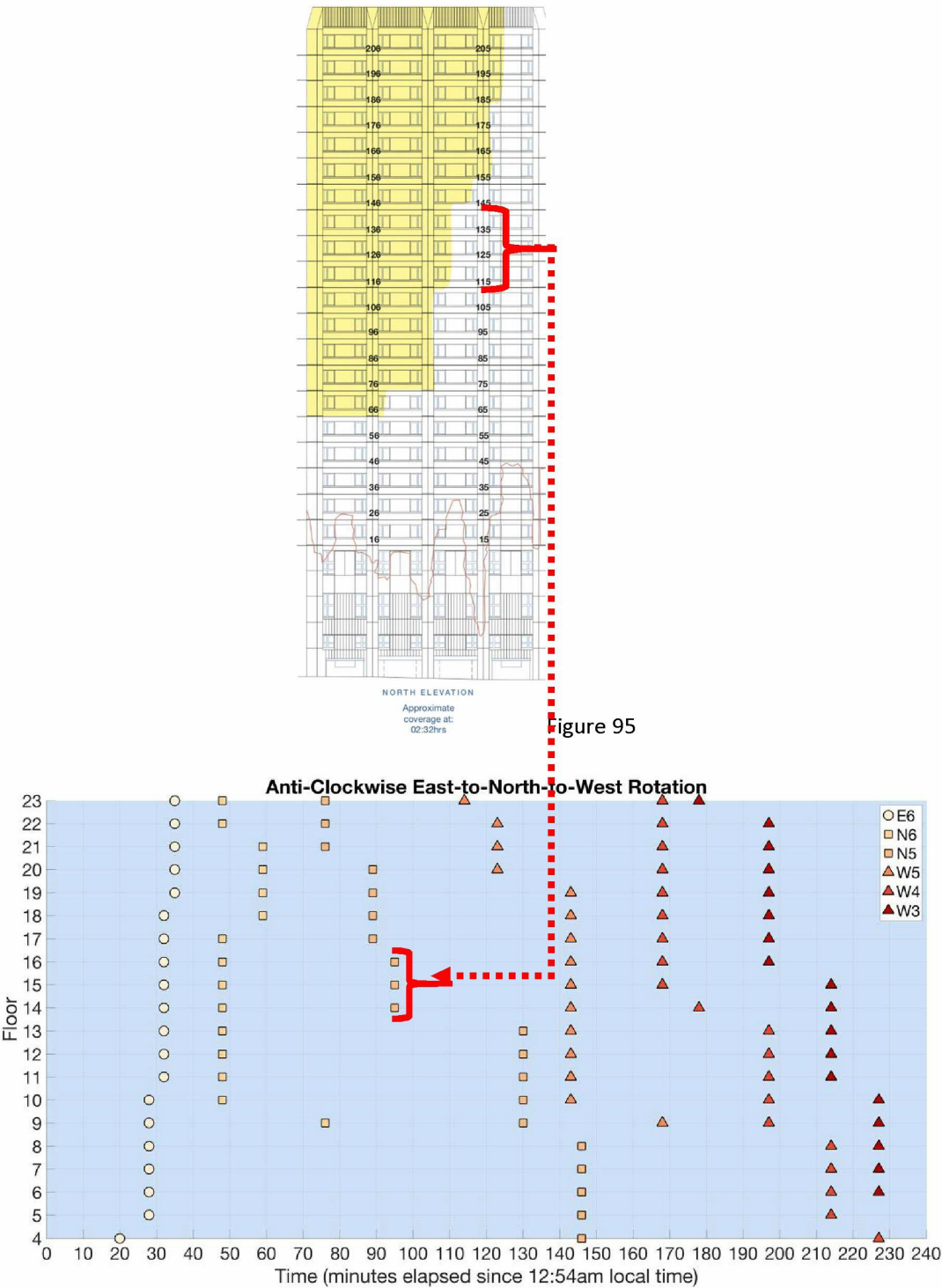


FIGURE 91: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 02:32 AM ON THE NORTH ELEVATION TOWER PLAN VIEW.

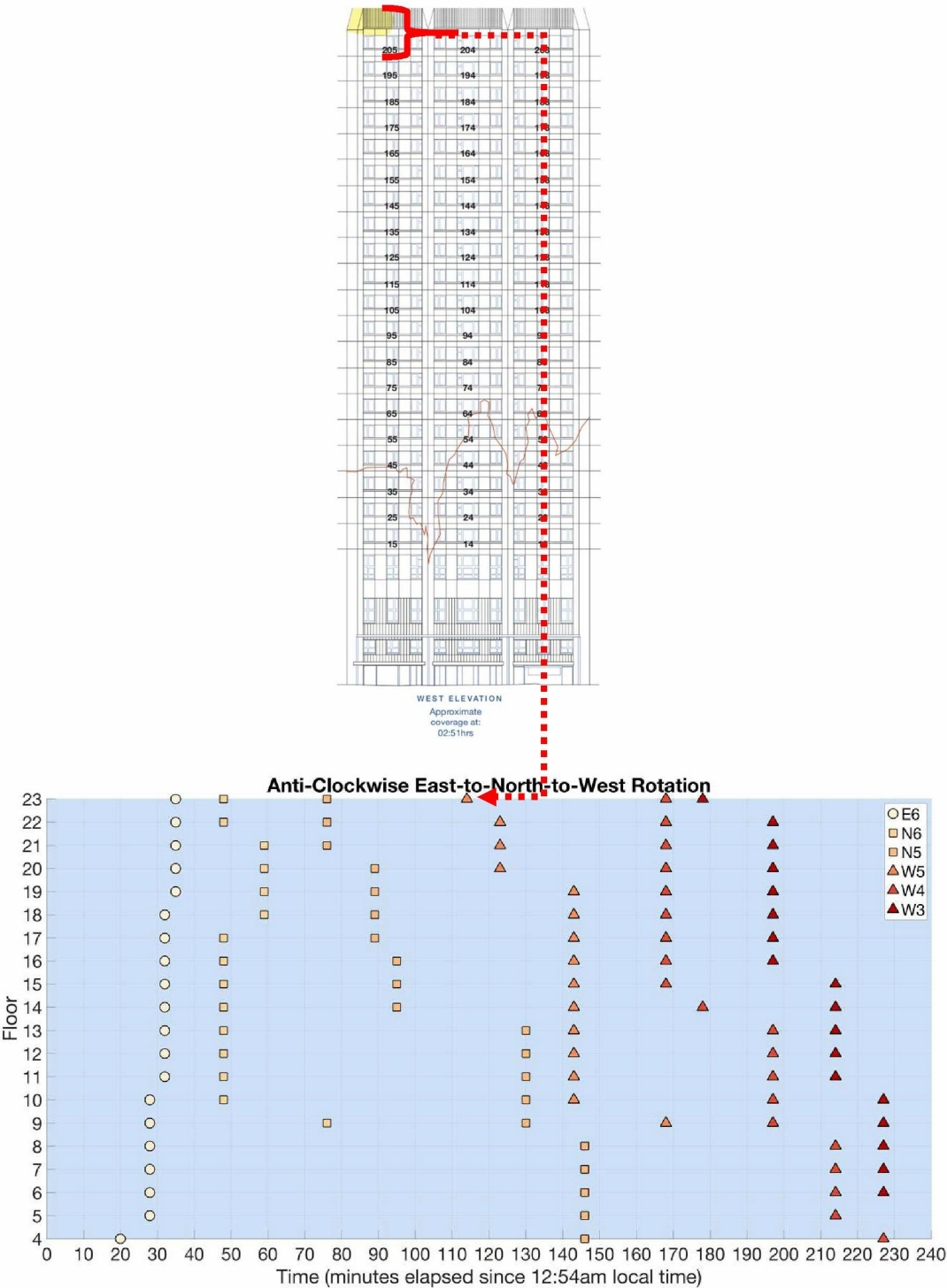


FIGURE 92: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 02:51 AM ON THE WEST ELEVATION TOWER PLAN VIEW.

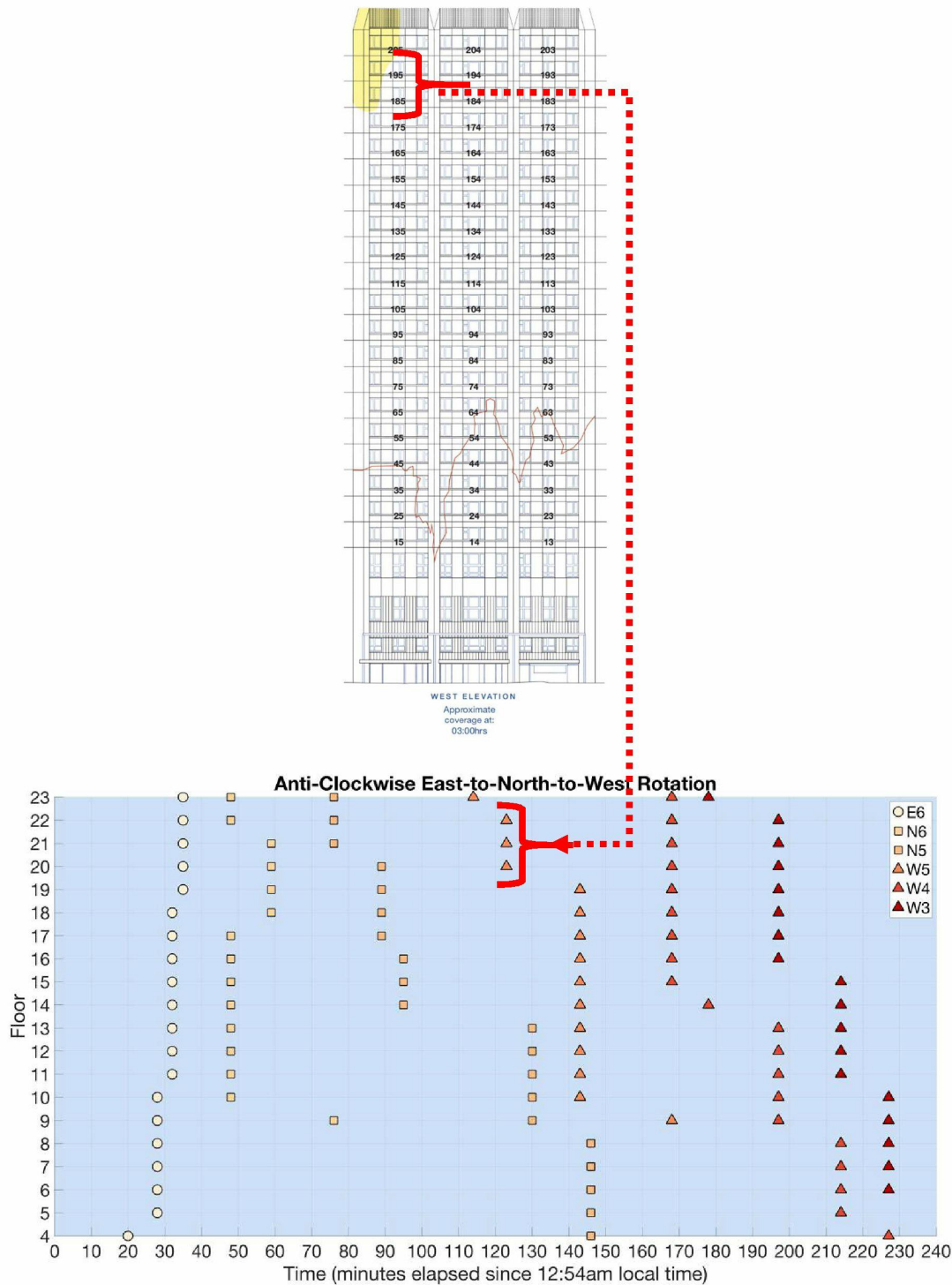


FIGURE 93: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 02:51 AM ON THE WEST ELEVATION TOWER PLAN VIEW.

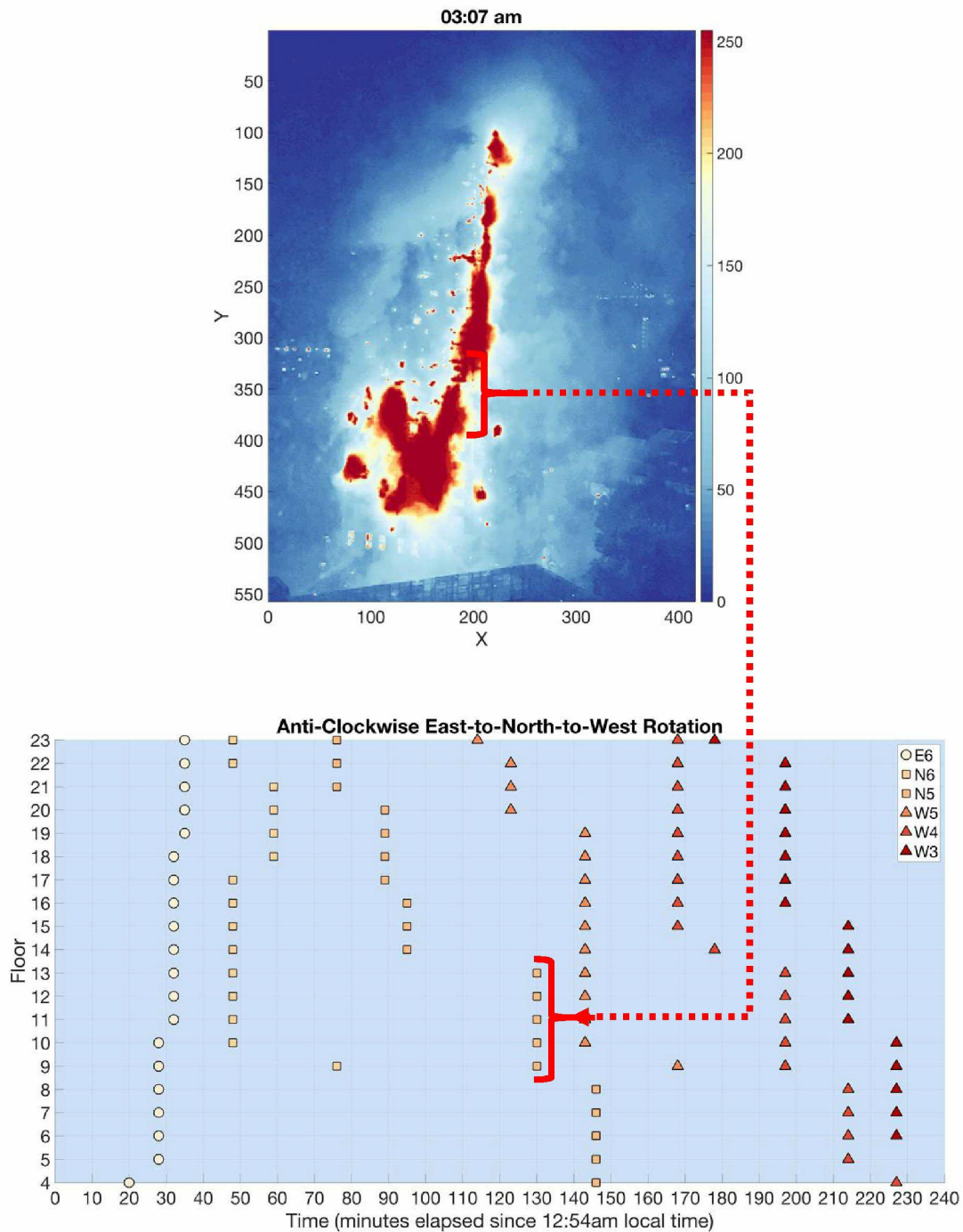


FIGURE 94: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 03:07 AM ON THE NORTH ELEVATION PROCESSED IMAGE (FIGURE 5H).

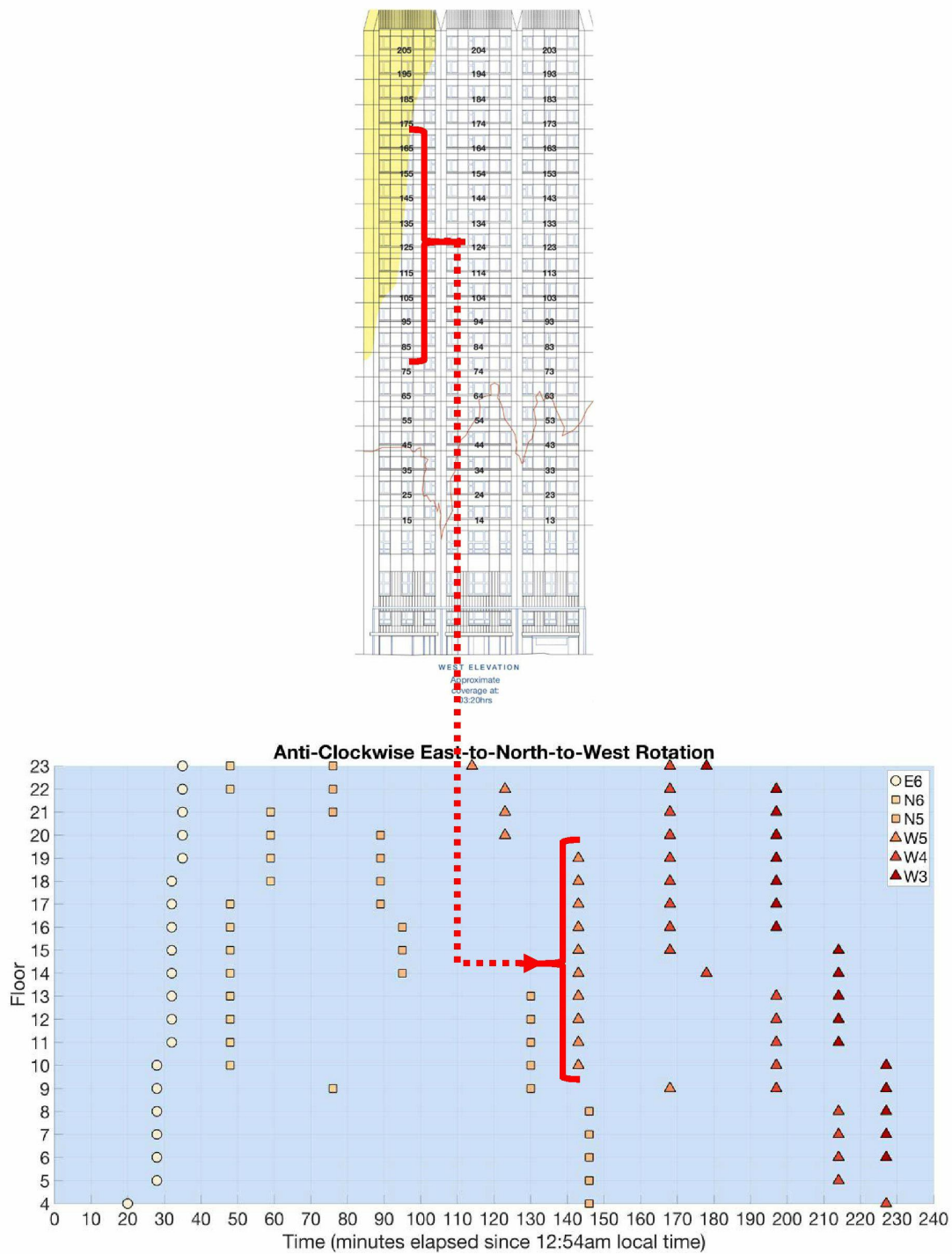


FIGURE 95: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 03:20 AM ON THE WEST ELEVATION TOWER PLAN VIEW.

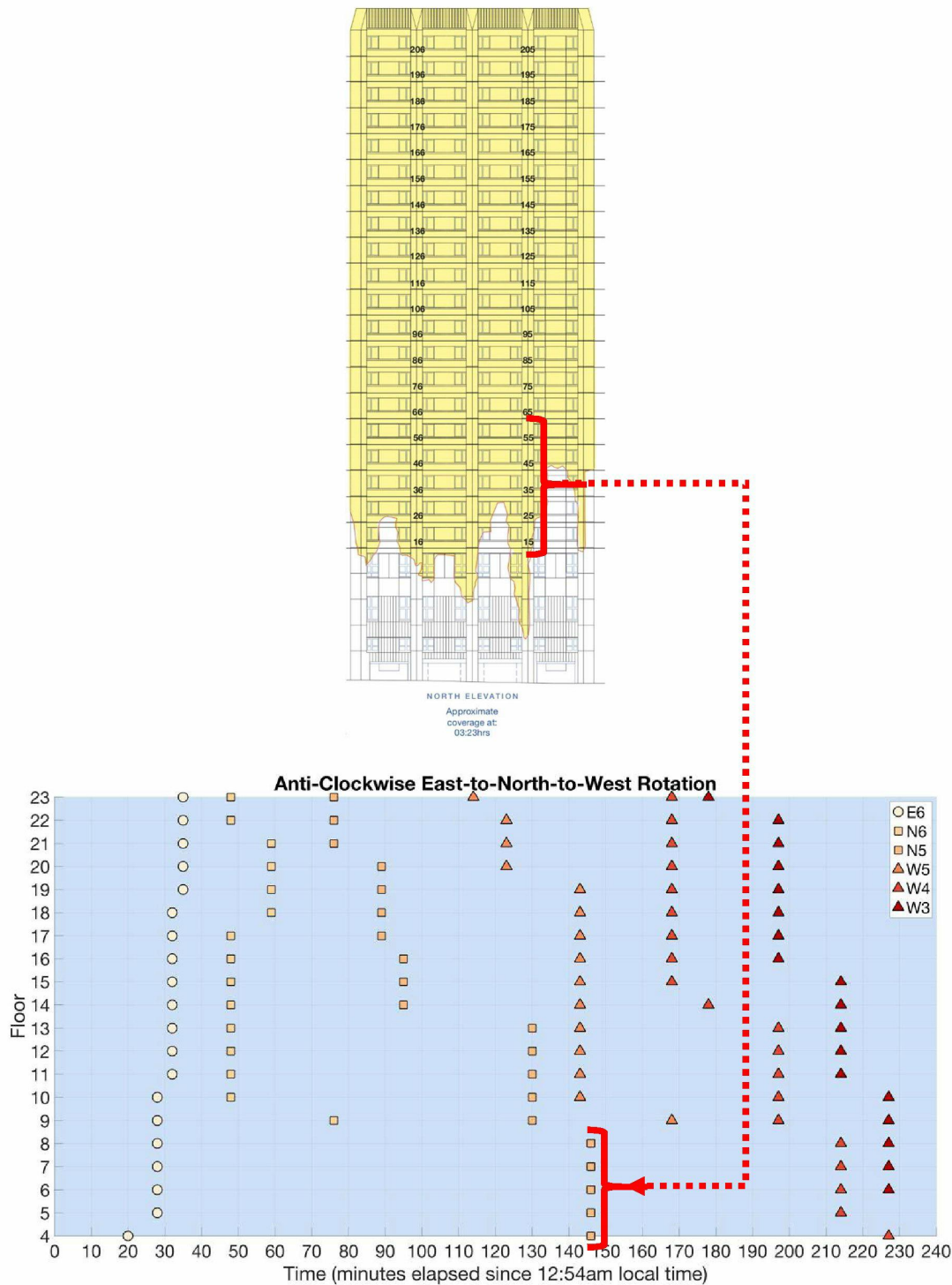


FIGURE 96: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 03:23 AM ON THE NORTH ELEVATION TOWER PLAN VIEW.

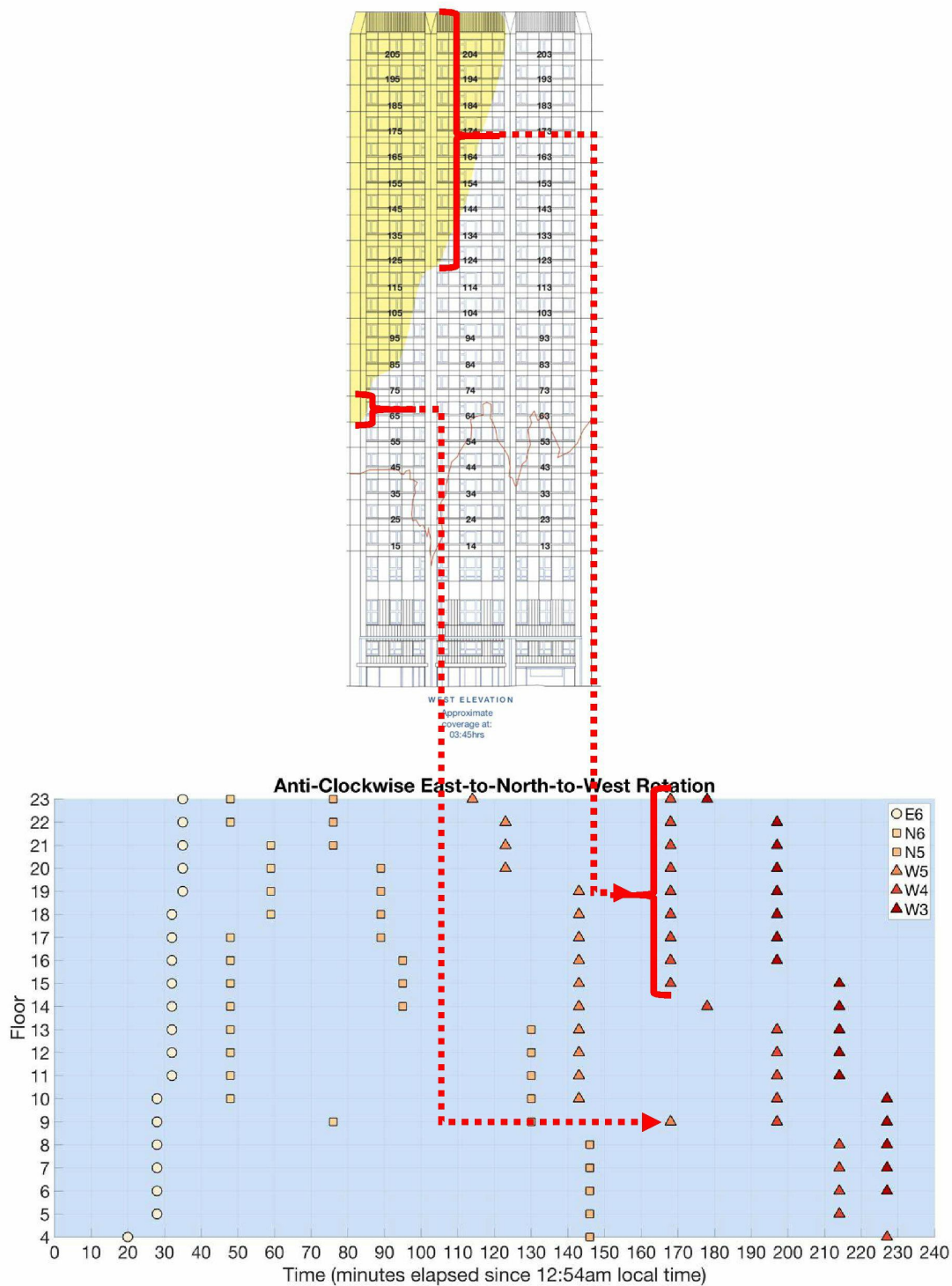


FIGURE 97: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROWS INDICATE THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 03:45 AM ON THE WEST ELEVATION TOWER PLAN VIEW.

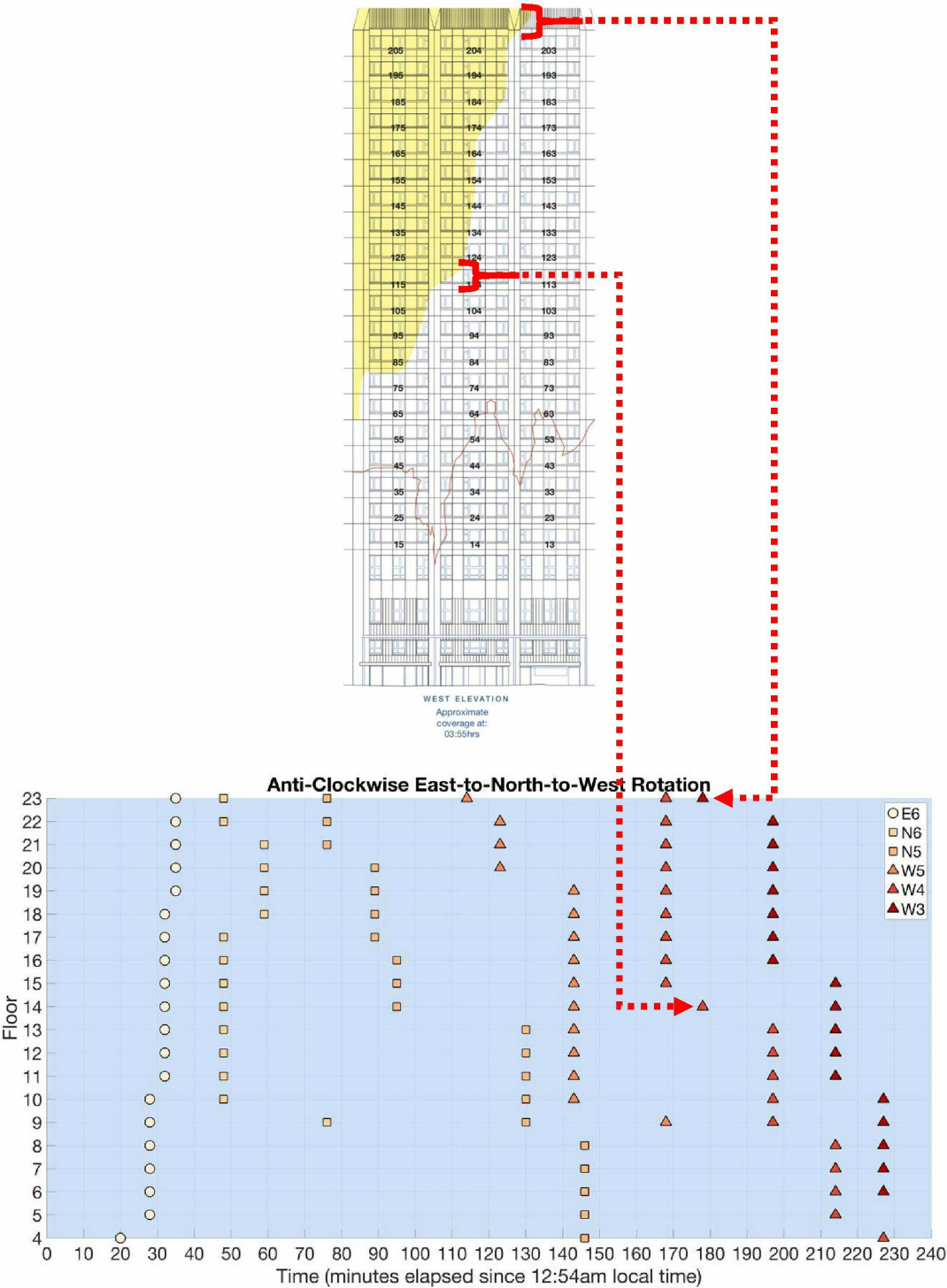


FIGURE 98: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROWS INDICATE THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 03:55 AM ON THE WEST ELEVATION TOWER PLAN VIEW.

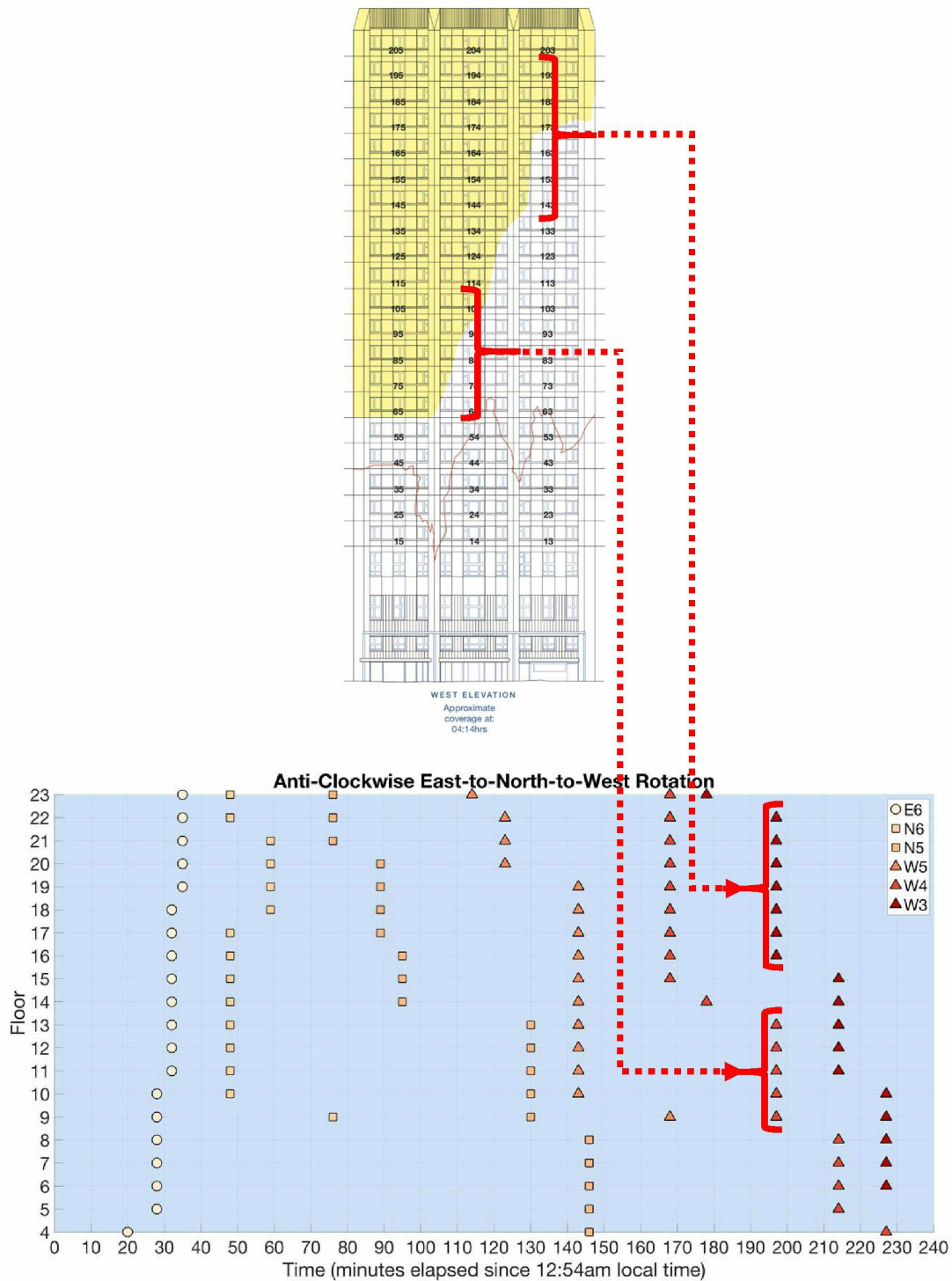


FIGURE 99: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROWS INDICATE THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 04:14 AM ON THE WEST ELEVATION TOWER PLAN VIEW.

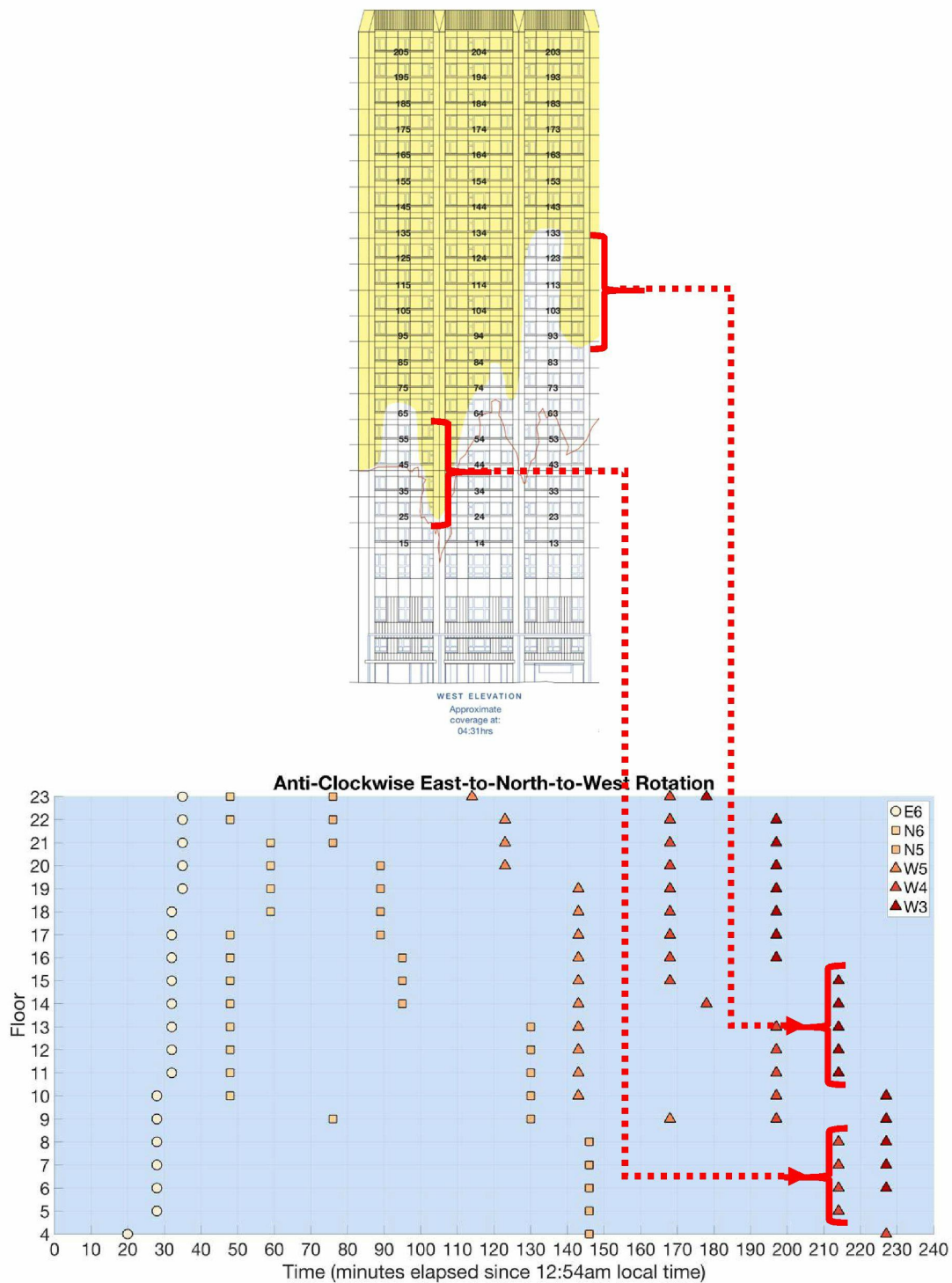


FIGURE 100: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROWS INDICATE THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 04:31 AM ON THE WEST ELEVATION TOWER PLAN VIEW.

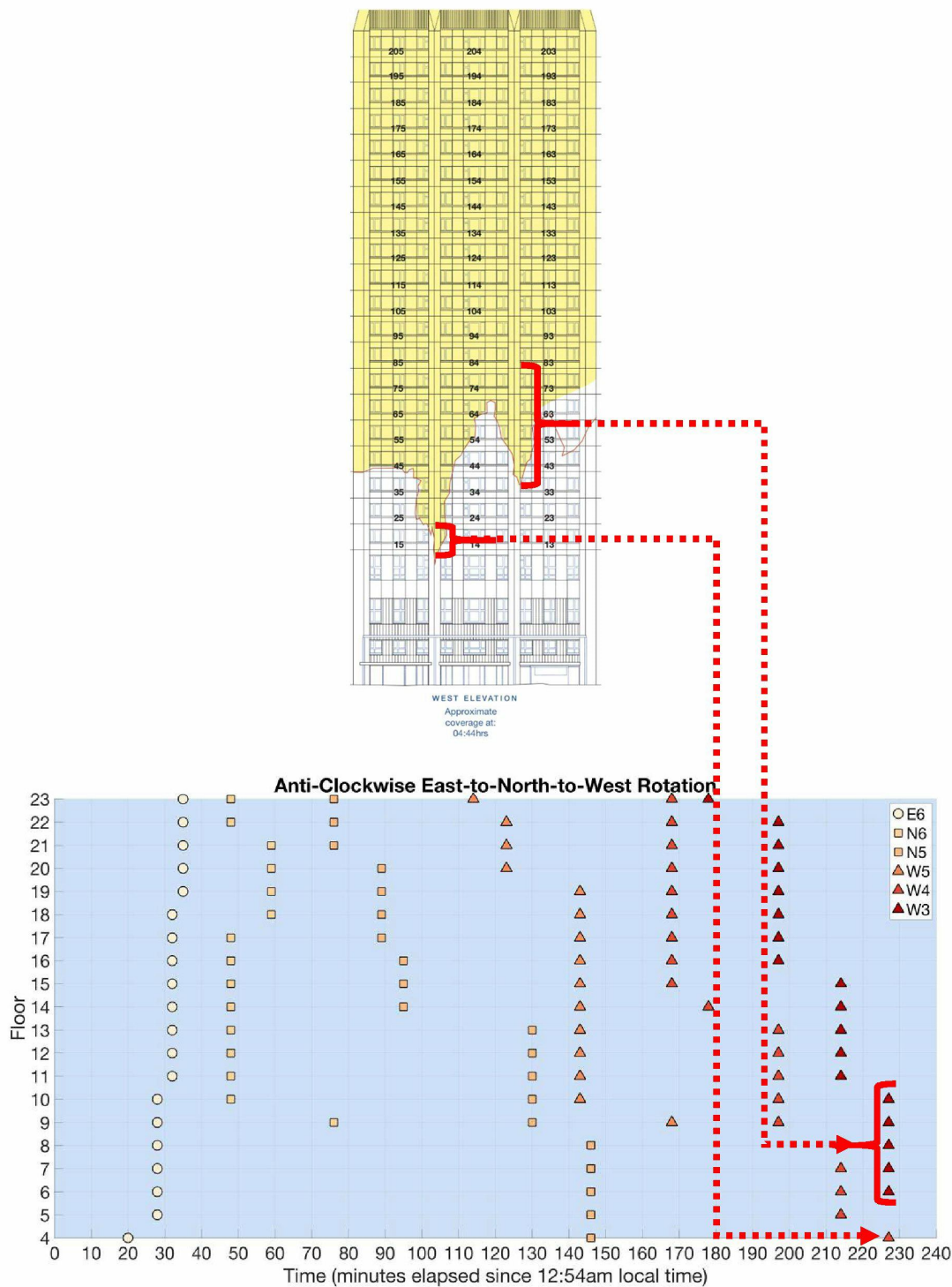


FIGURE 101: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E), NORTHERN (N) AND WESTERN (W) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROWS INDICATE THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 04:44 AM ON THE WEST ELEVATION TOWER PLAN VIEW.

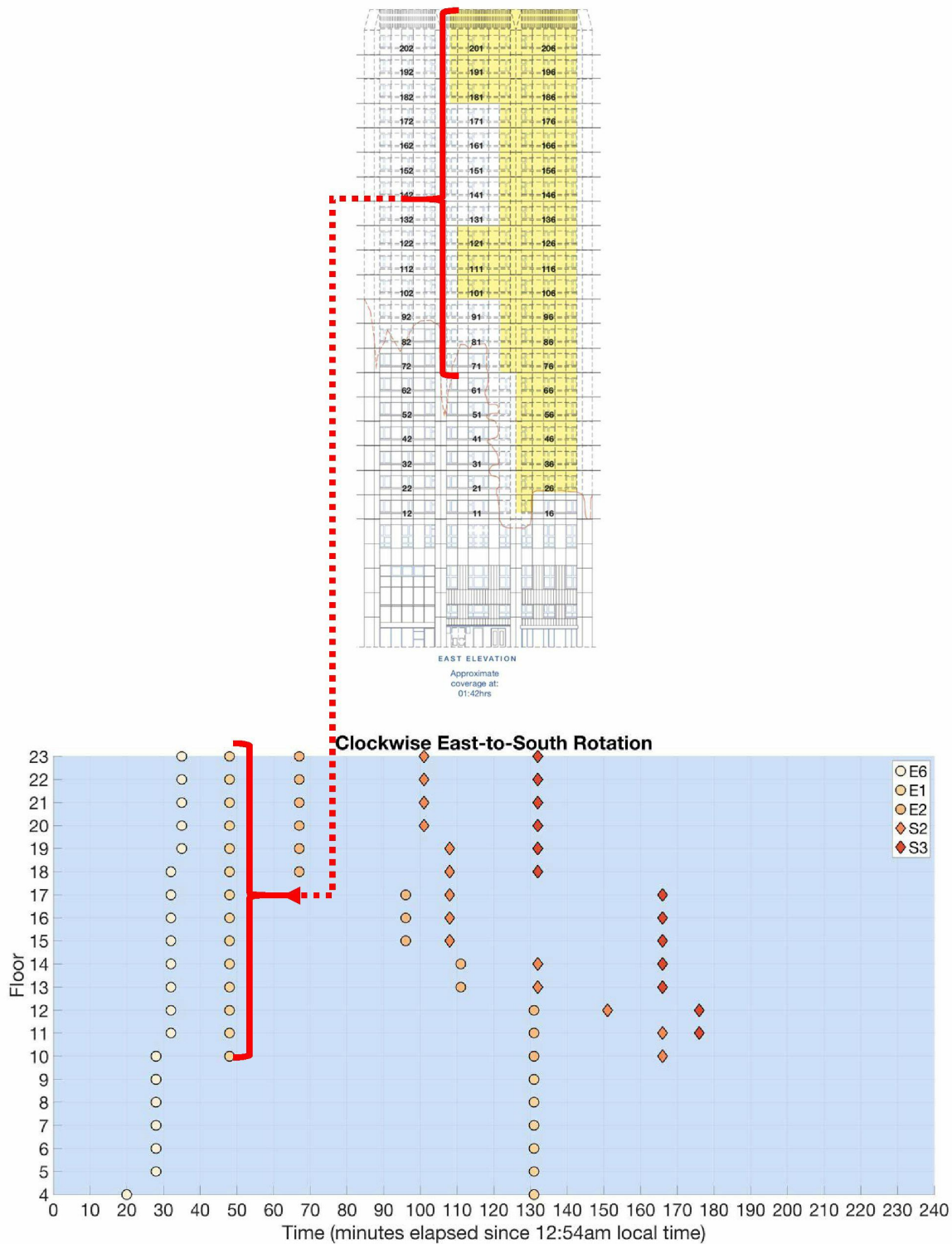


FIGURE 102: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E) AND SOUTHERN (S) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 01:42 AM ON THE EAST ELEVATION TOWER PLAN VIEW.

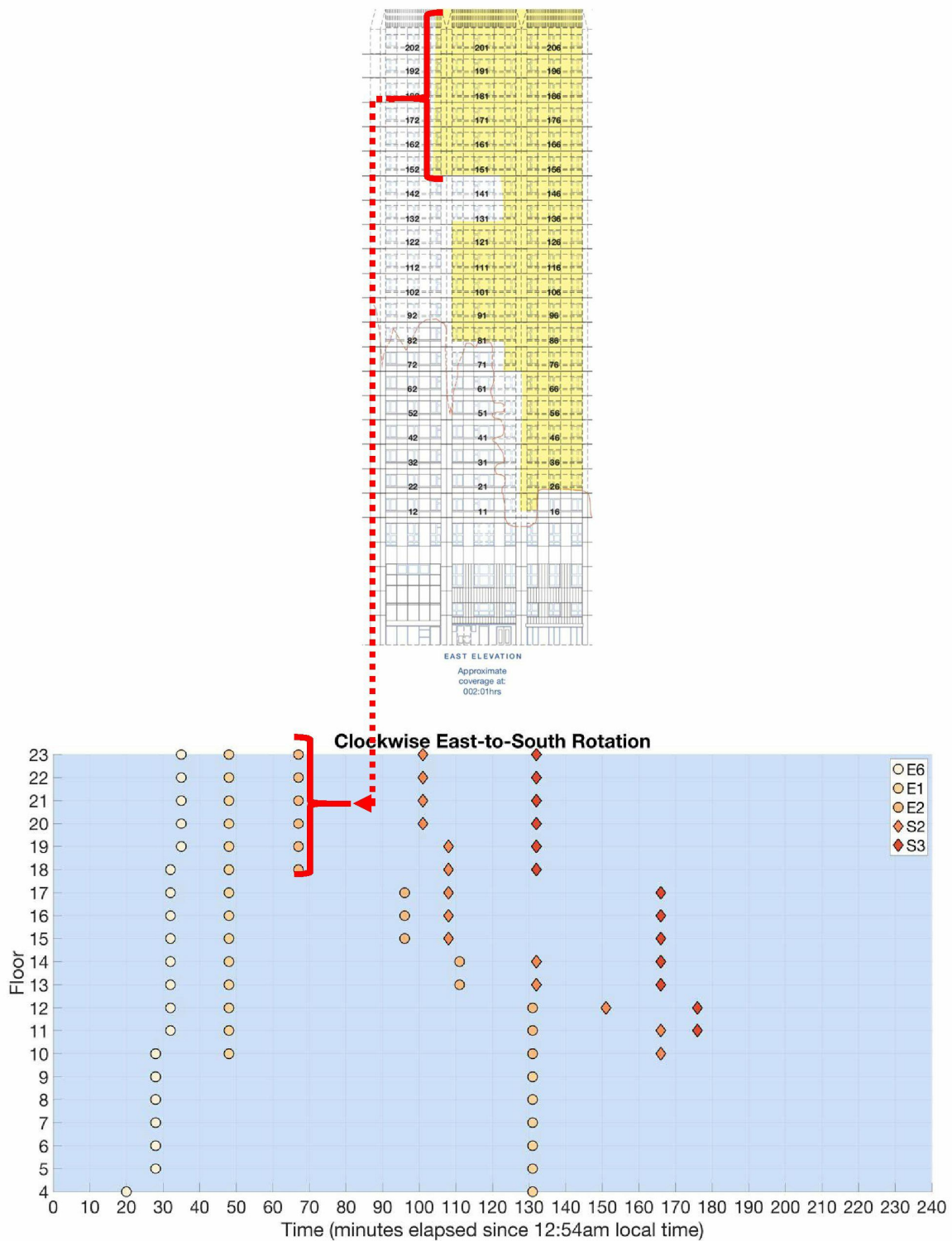


FIGURE 103: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E) AND SOUTHERN (S) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 02:01 AM ON THE EAST ELEVATION TOWER PLAN VIEW.

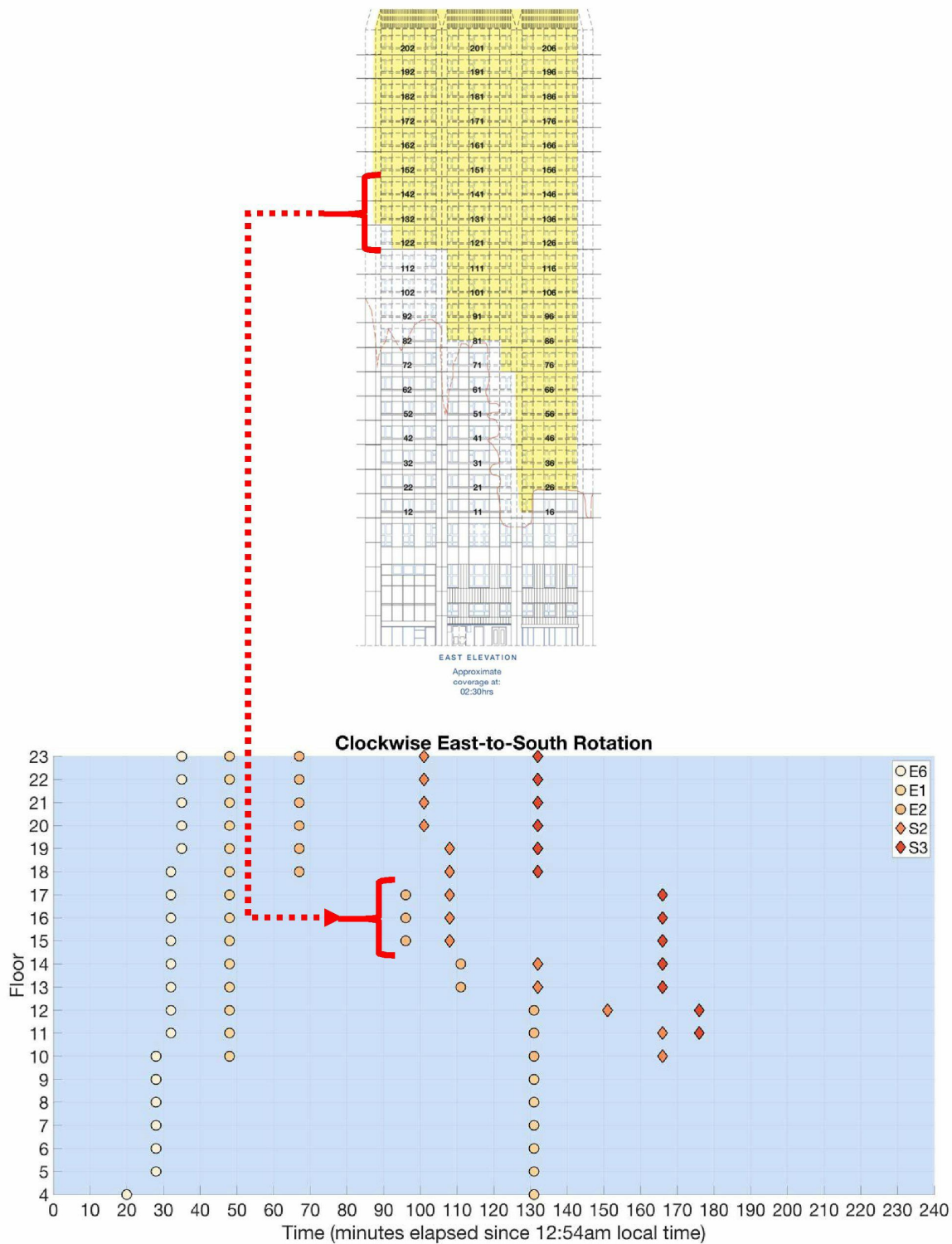


FIGURE 104: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E) AND SOUTHERN (S) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 02:30 AM ON THE EAST ELEVATION TOWER PLAN VIEW.

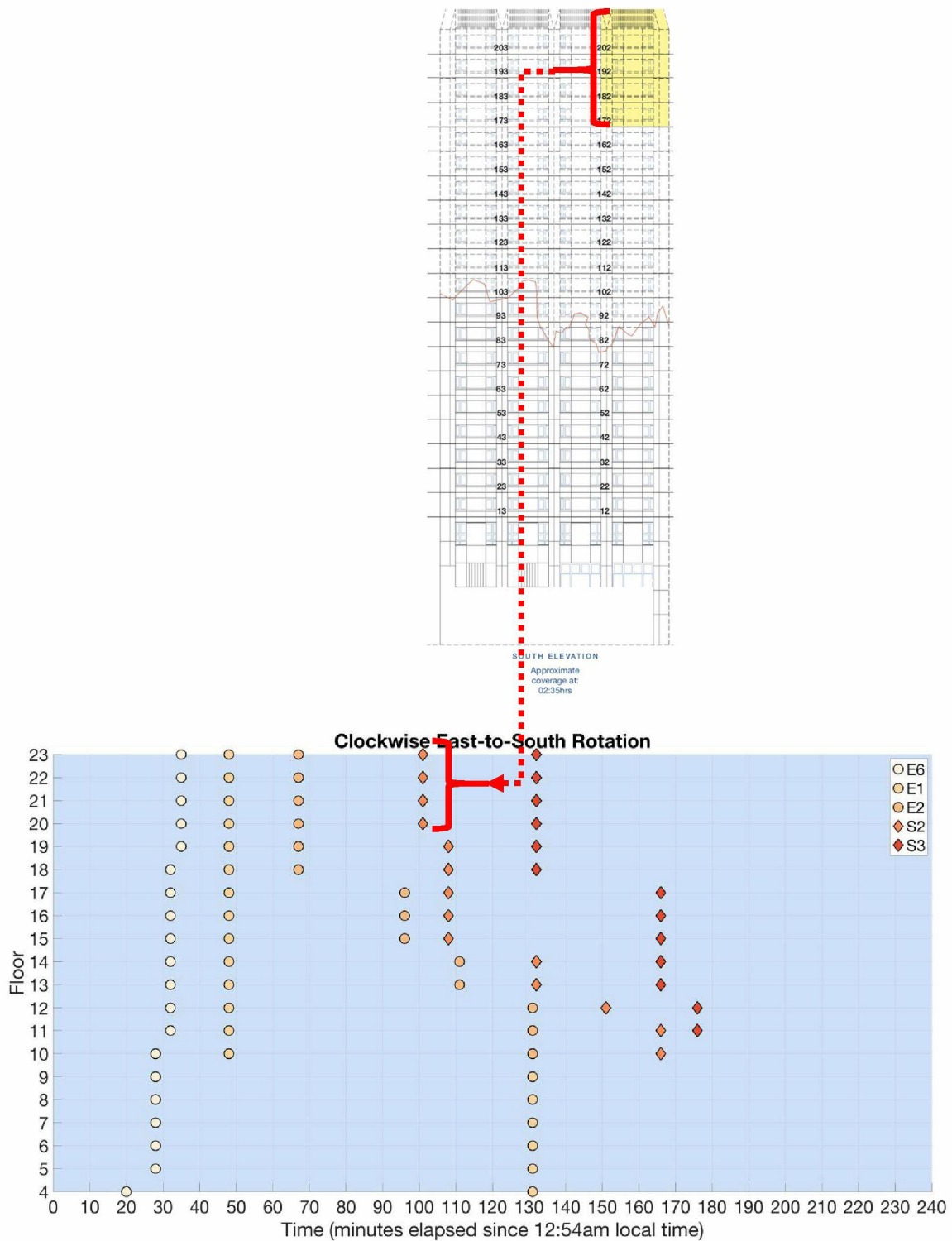


FIGURE 105: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E) AND SOUTHERN (S) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 02:35 AM ON THE SOUTH ELEVATION TOWER PLAN VIEW.

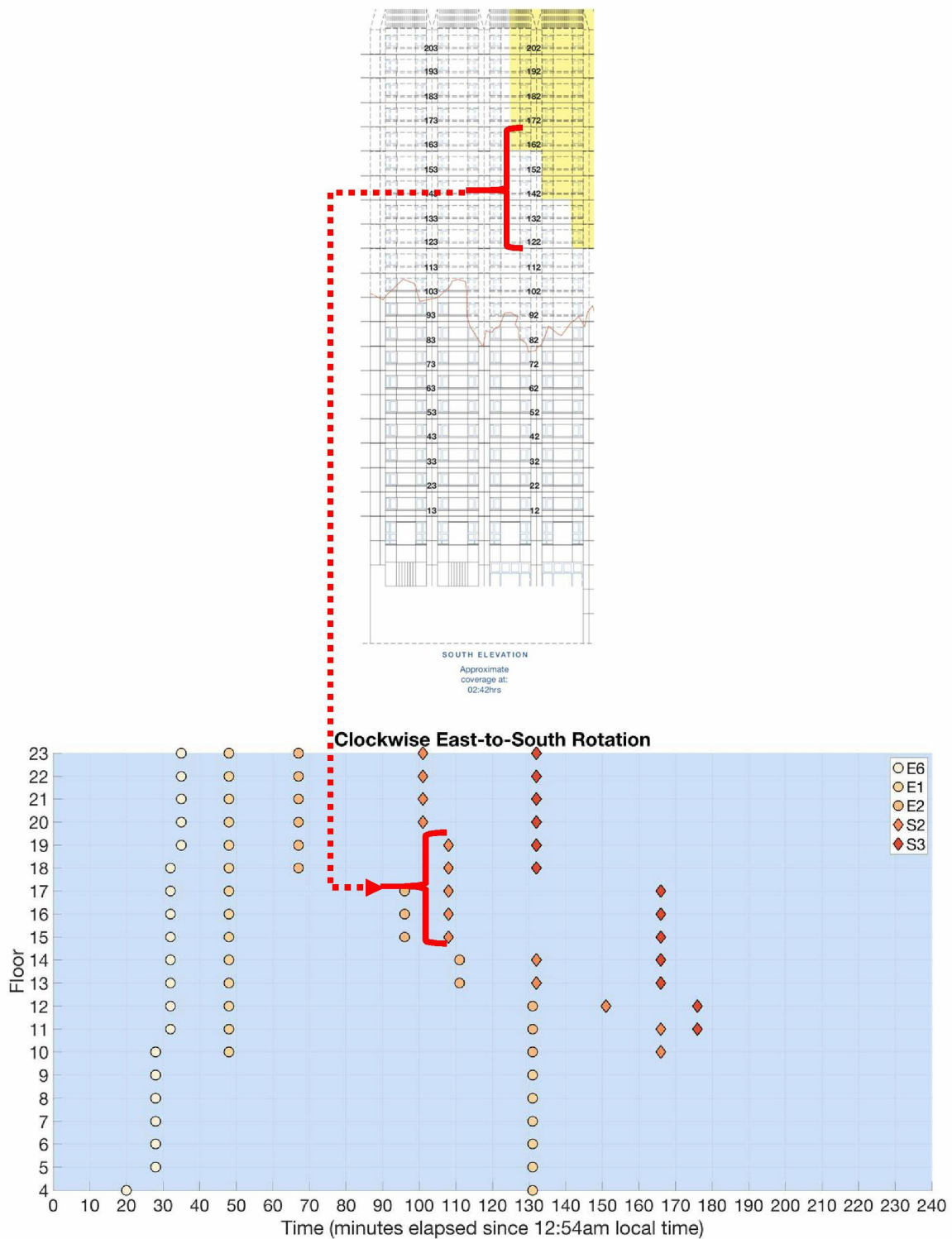


FIGURE 106: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E) AND SOUTHERN (S) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 02:42 AM ON THE SOUTH ELEVATION TOWER PLAN VIEW.

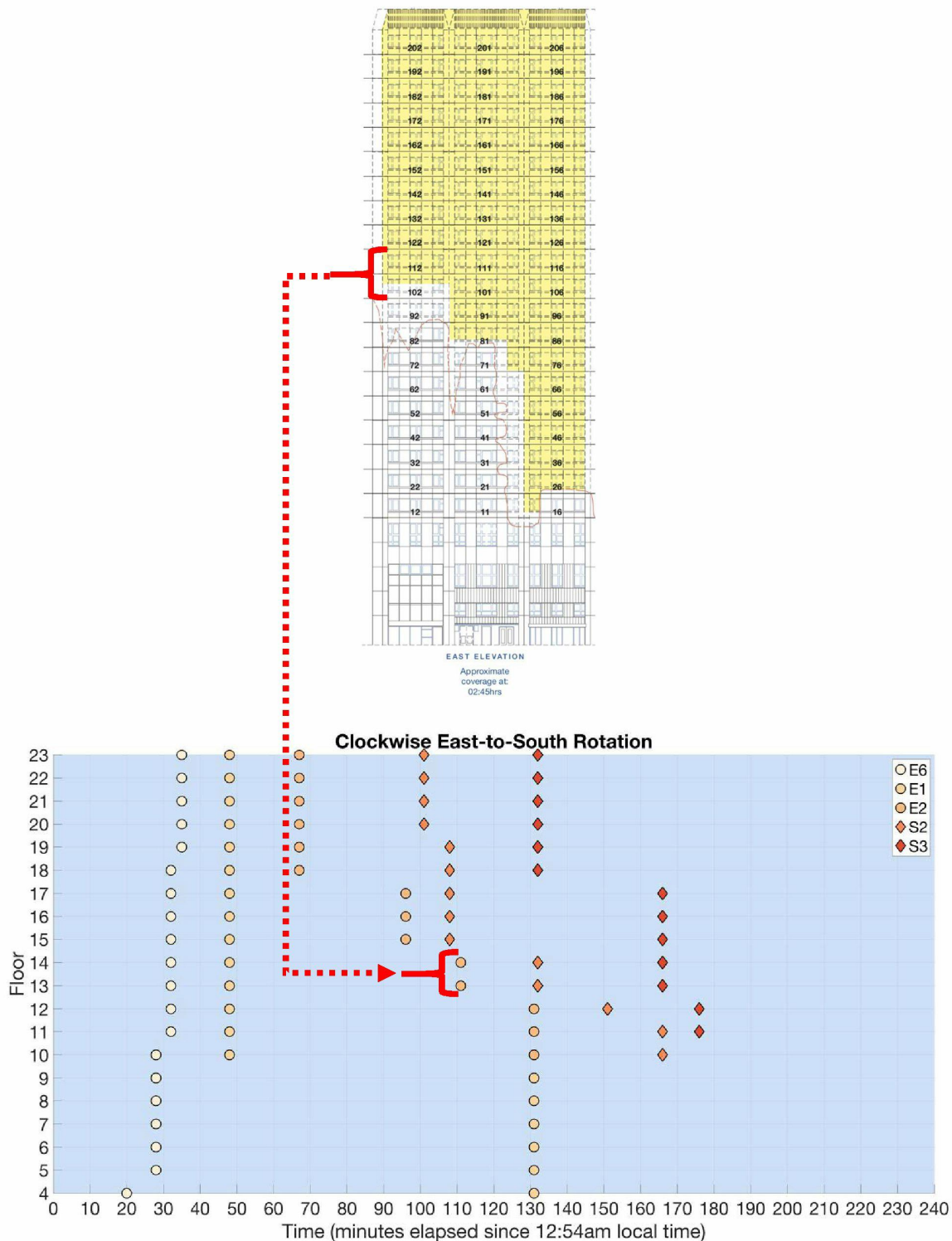


FIGURE 107: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E) AND SOUTHERN (S) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 02:45 AM ON THE EAST ELEVATION TOWER PLAN VIEW.

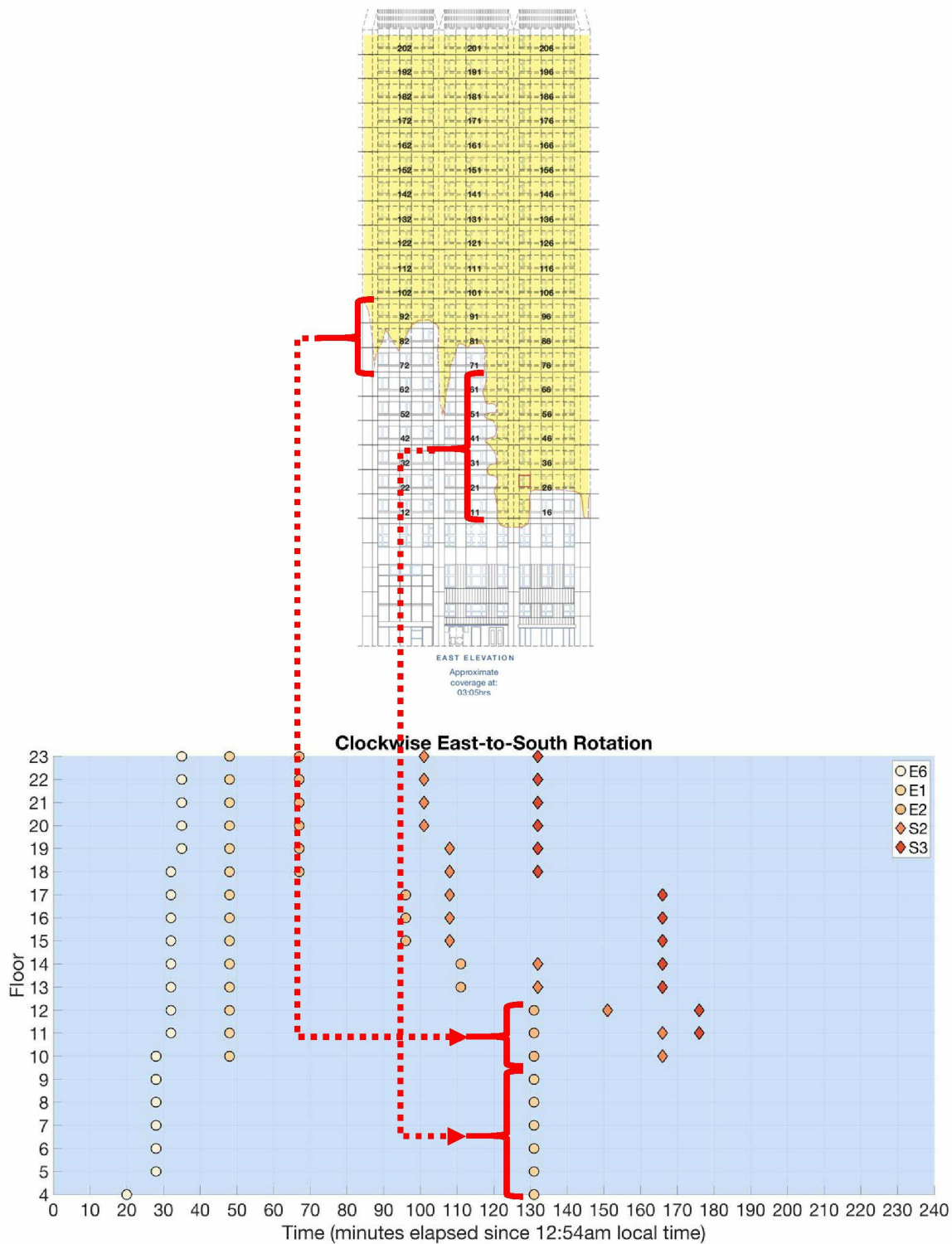


FIGURE 108: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E) AND SOUTHERN (S) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROWS INDICATE THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 03:05 AM ON THE EAST ELEVATION TOWER PLAN VIEW.

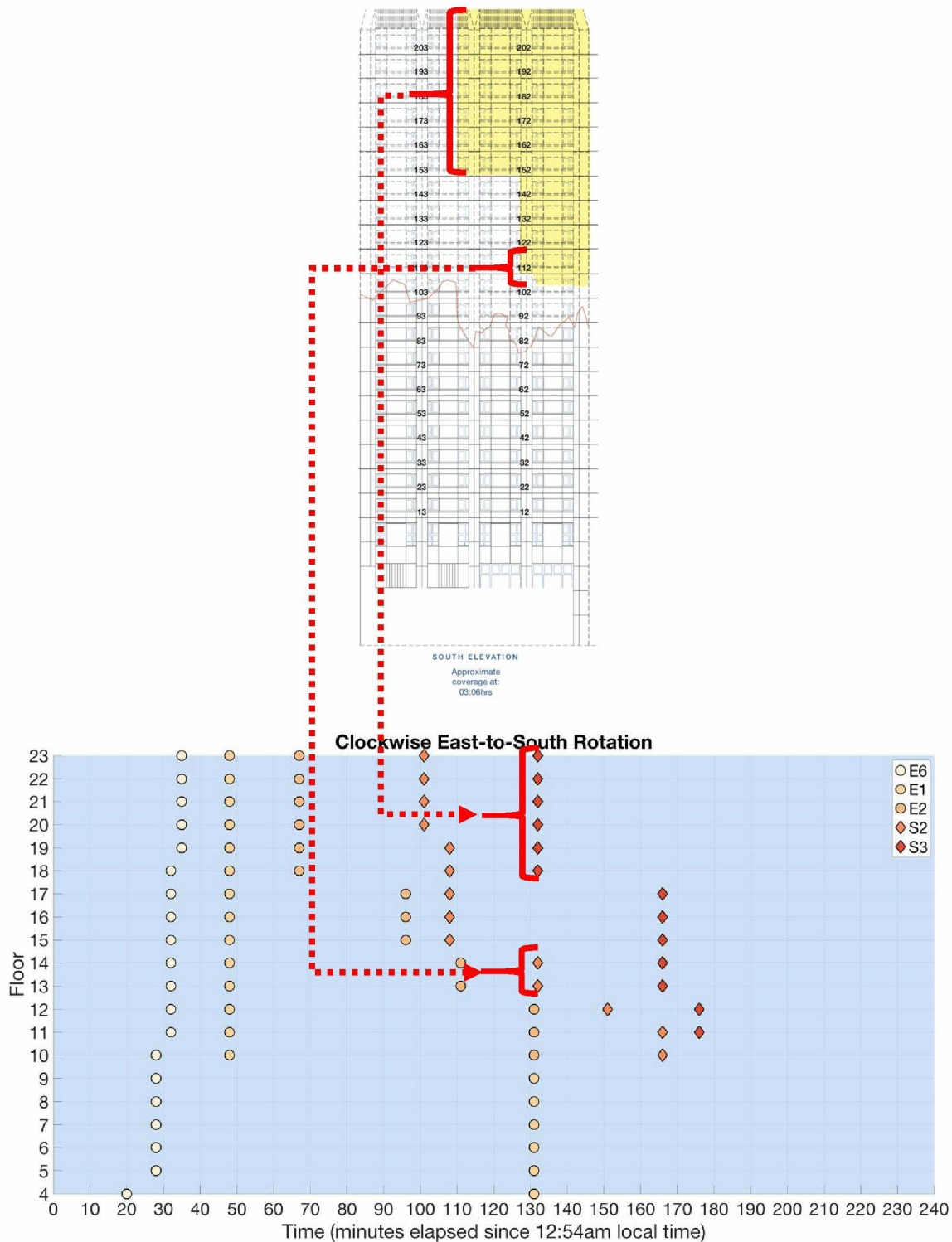


FIGURE 109: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E) AND SOUTHERN (S) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROWS INDICATE THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 03:06 AM ON THE SOUTH ELEVATION TOWER PLAN VIEW.

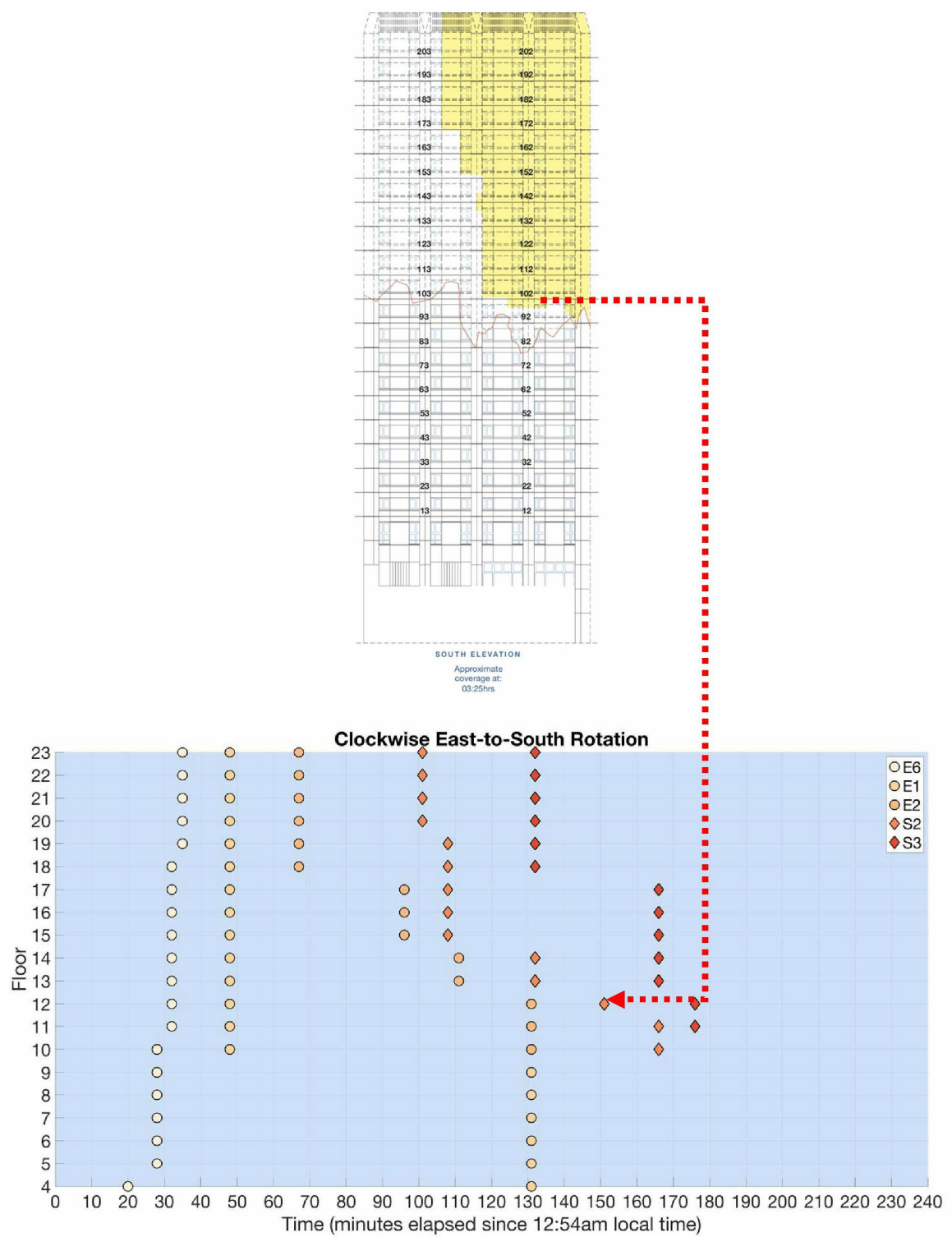


FIGURE 110: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E) AND SOUTHERN (S) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 03:25 AM ON THE SOUTH ELEVATION TOWER PLAN VIEW.

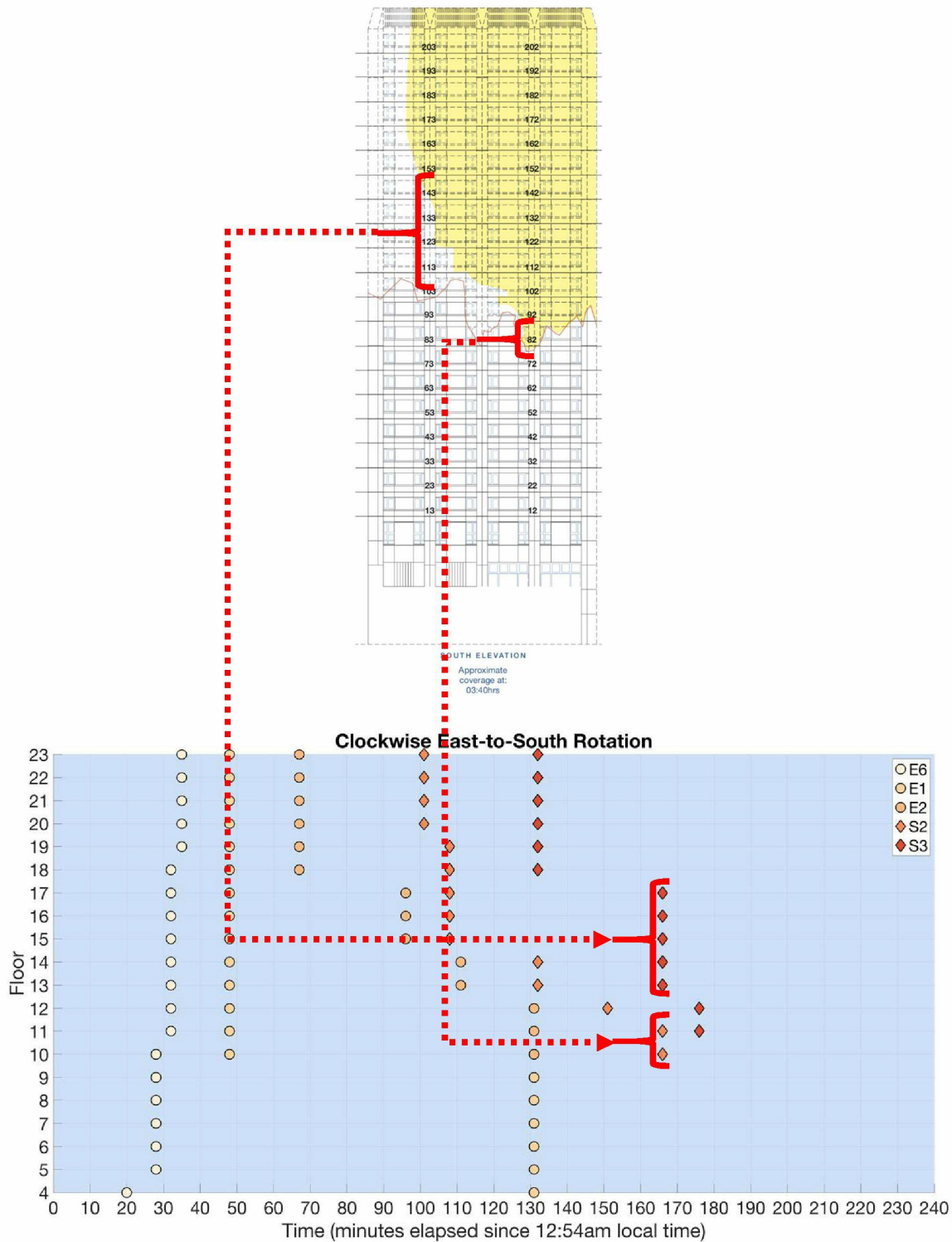


FIGURE 111: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E) AND SOUTHERN (S) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROWS INDICATE THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 03:40 AM ON THE SOUTH ELEVATION TOWER PLAN VIEW.

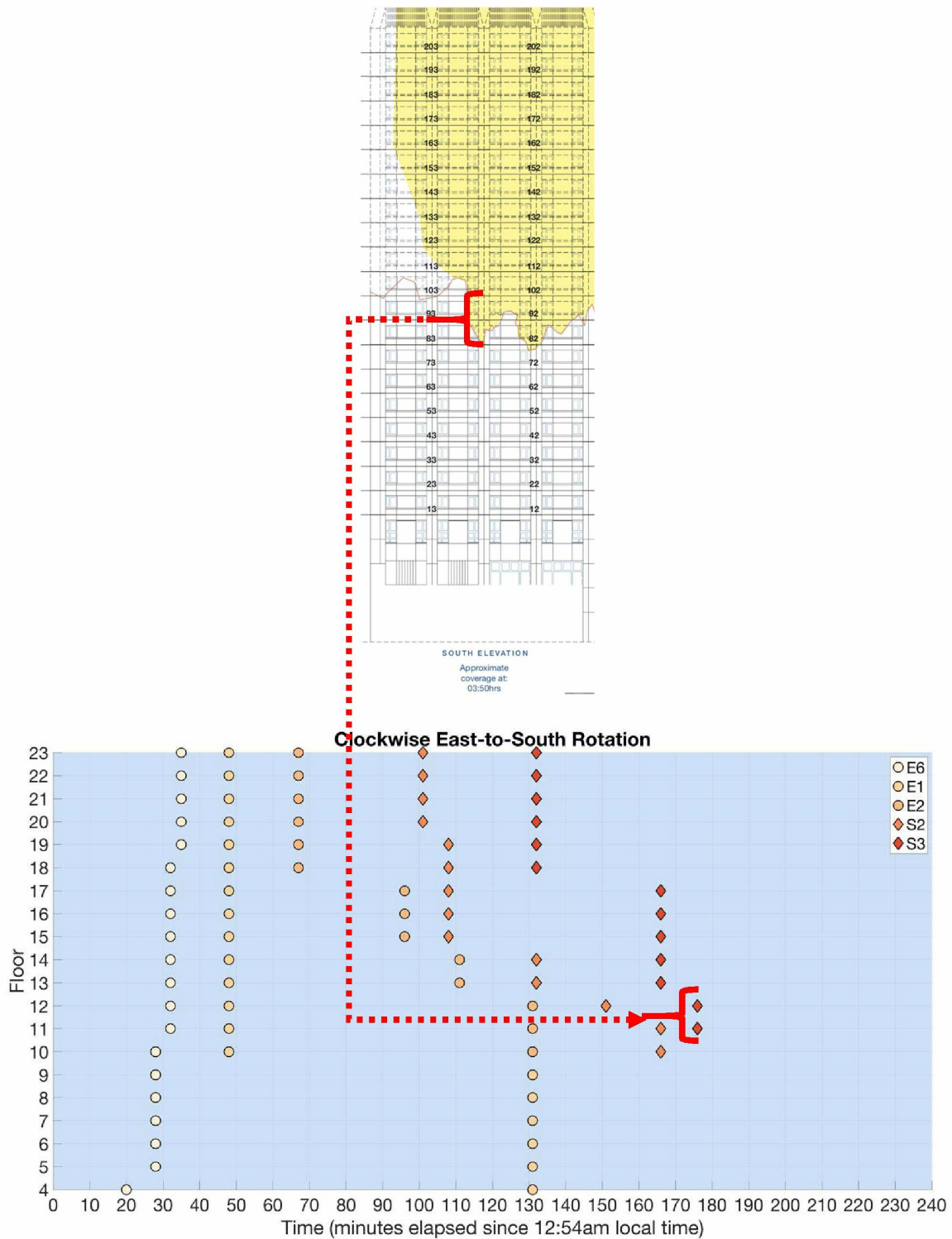
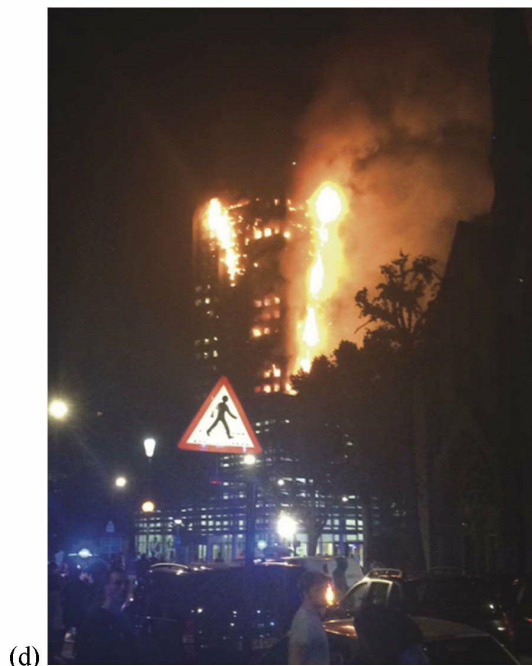
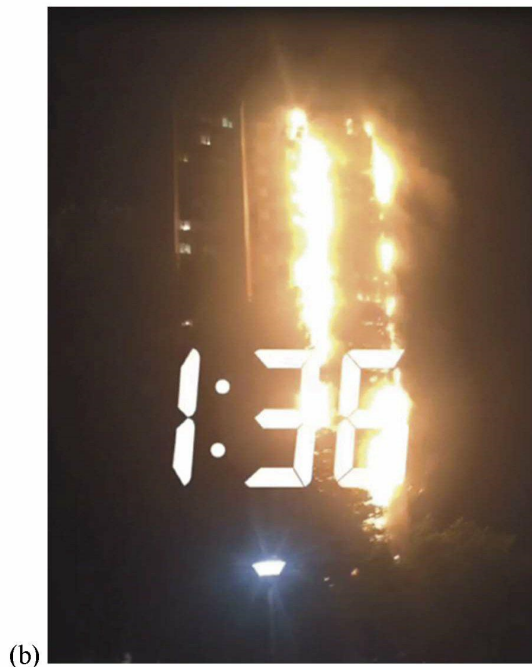
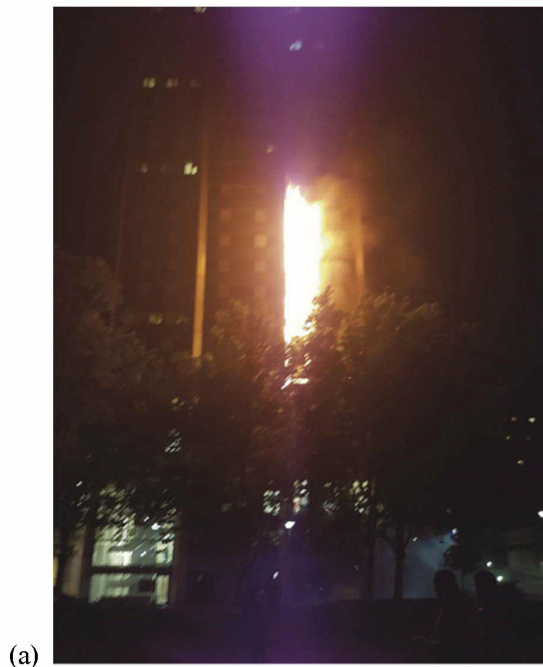


FIGURE 112: TIME HISTORY OF EXTERNAL FLAME SPREAD ON THE EASTERN (E) AND SOUTHERN (S) FACADES. THE STACK OF FLATS IMPACTED BY THE EXTERNAL FLAME SPREAD ARE INDICATED USING NUMBERS 1-6 APPENDED TO THE FACADE DESCRIPTOR IN THE LEGEND. THE RED ARROW INDICATES THE ESTIMATED POSITION OF EXTERNAL FLAMES AT 03:50 AM ON THE SOUTH ELEVATION TOWER PLAN VIEW.

Additional photos showing lateral and vertical flame spread

East Facade



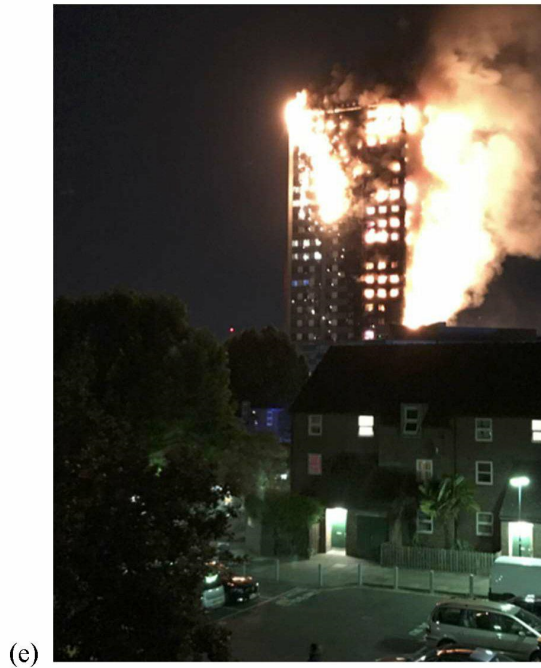
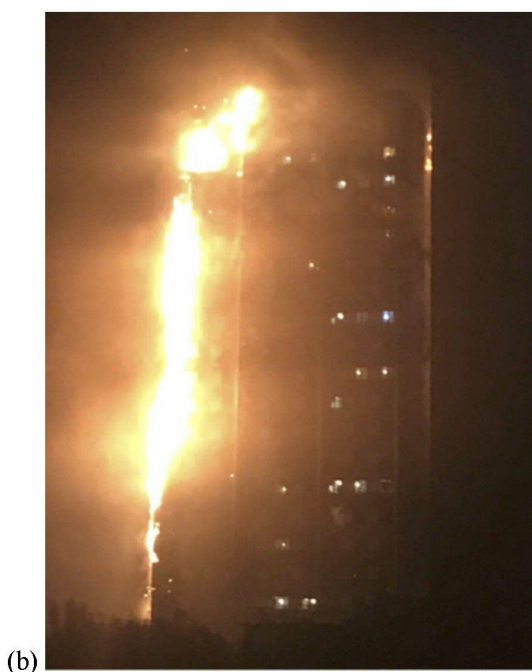


FIGURE 113: ORIGINAL PUBLIC FOOTAGE OF LATERAL AND VERTICAL (UPWARD AND DOWNWARD) FLAME SPREAD ON THE EAST FACADE OF GRENFELL TOWER AT (A) 01:22 AM; (B) 01:36 AM; (C) 01:52 AM; (D) 02:08 AM; (E) 02:22 AM; AND (F) 02:53 AM RESPECTIVELY. PHOTOS WERE SOURCED FROM MET00008024, PAGES 28-29.

West Facade



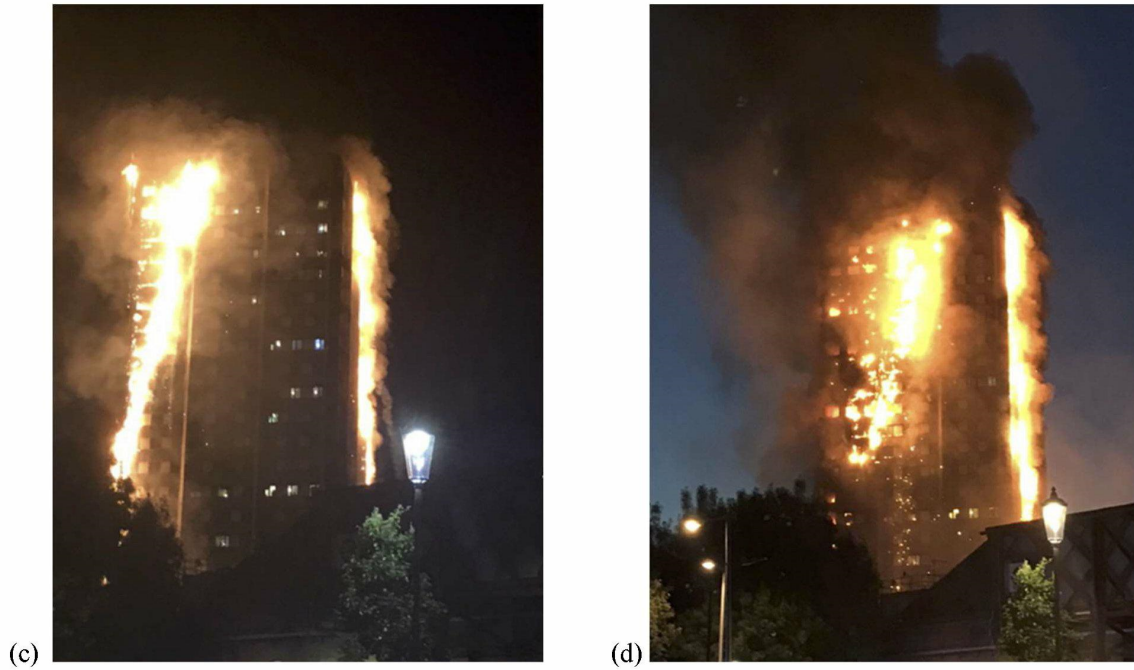


FIGURE 114: ORIGINAL PUBLIC FOOTAGE OF LATERAL AND VERTICAL (DOWNWARD) FLAME SPREAD ON THE WEST FACADE OF GRENFELL TOWER AT (A) 02:50 AM; (B) 03:15 AM; (C) 03:20 AM; AND (D) 03:48 AM RESPECTIVELY. PHOTOS WERE SOURCED FROM MET00008024, PAGE 59.



FIGURE 115: IMAGES FROM THE WEST FAÇADE CORRESPONDING TO (A) 03:20 AM; AND (B) 03:48 AM RESPECTIVELY.

APPENDIX F. STRUCTURAL ANALYSIS

The properties defining loss of strength in rebar are given in Euro Code 2 [46] and shown in the plot in Figure 116. The plot indicates that typical rebar begins to lose strength at 300°C, losing 50% of its strength by 550°C, this latter threshold typically taken as a conservative failure criterion. Eurocode 2 also gives the reduction in concrete strength as a function of temperature, shown in Figure 117.

The range of thermal loading applied in the model is taken from Section 5.4 of this report, which represents estimated characteristic, upper and lower bound, compartment temperatures in a typical one-bedroom flat in the Grenfell Tower. The growth phase of the fires is ignored and gas phase temperature boundary conditions between 850°C and 1000°C are applied.

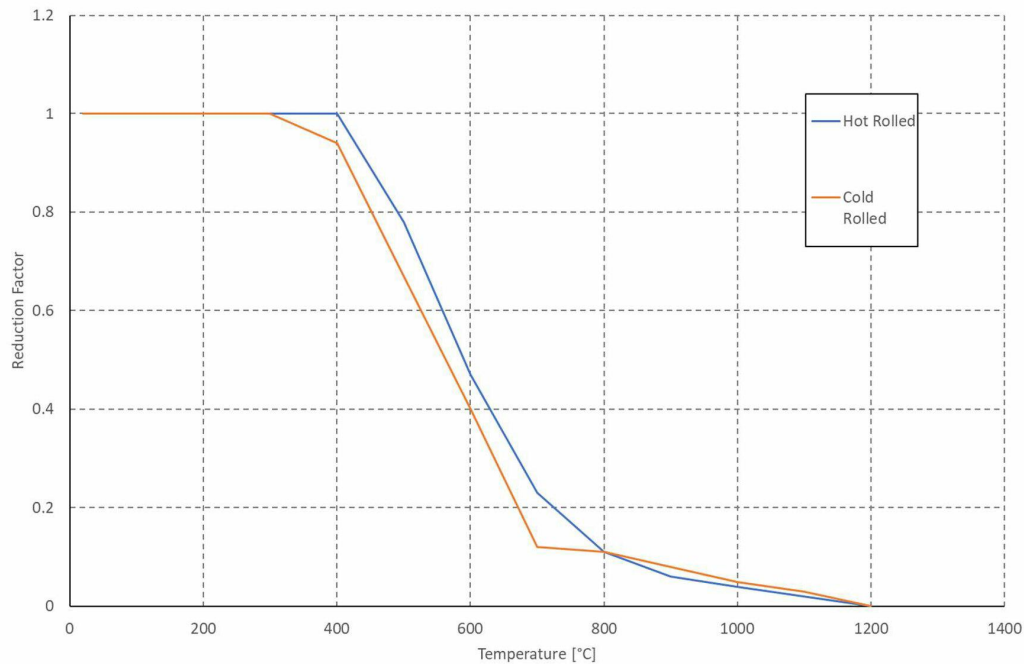


FIGURE 116: Strength reduction factor of typical rebar steels as a function of temperature according to [46].

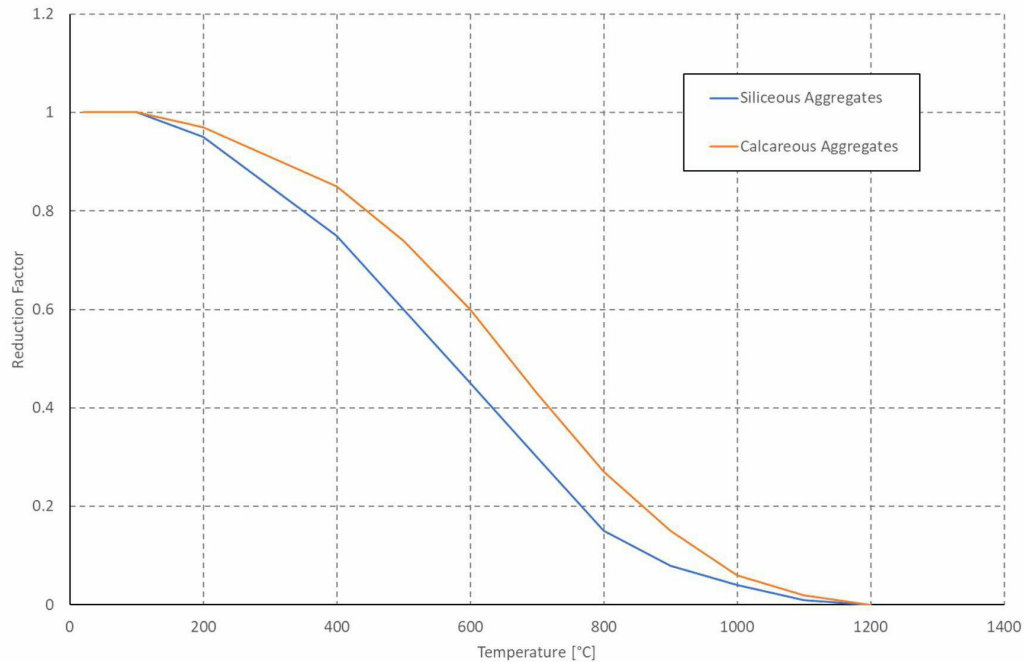


FIGURE 117: Strength reduction factors of normal weight concretes as a function of temperature according to [46].

ONE-DIMENSIONAL FINITE DIFFERENCE MODEL

The finite difference heat transfer model by Emmons [47] and Dusingberre [48] is described by Maluk [49]. It breaks the concrete into finite thicknesses for which the energy entering and leaving each thickness over a fixed period of time is resolved to define the resultant temperature of that thickness.

Notation is such that the subscript represents the element number (1 for the surface, 2 for the next layer and so on) and the superscript represents the timestep. The temperature of each node at the next timestep, (i+1), is defined as a function of the conditions at the current timestep, i. At the exposed surface, Node J=1, the Temperature at the following timestep i+1 is defined as:

$$T_1^{i+1} = T_1^i + \frac{2 \cdot \Delta t}{(\rho \cdot c)_1 \Delta x} \cdot \left[\dot{q}_{abs}^i - \left(\frac{\lambda_1^i + \lambda_2^i}{2} \right) \cdot \left(\frac{T_1^i - T_2^i}{\Delta x} \right) \right]$$

EQUATION 24

Where λ_j^i is the thermal conductivity of the material of element j at time step i. T_j^i is the temperature of element j at timestep i, ρ is the density of the material that forms the element, c is the specific heat capacity of the material that forms the element, Δx is the thickness of the element, and Δt is the timestep. \dot{q}_{abs}^i is the flux of heat from the fire environment to the exposed concrete surface and is defined as:

3352

$$3353 \quad \dot{q}_{abs}^i = h_T(T_g^i - T_1^i)$$

3354

EQUATION 25

3355

3356 Where h_t is the total heat transfer coefficient ($45 \text{ W/m}^2 \cdot \text{K}$), T_g is the exposure temperature (K), and T_1
 3357 is the temperature of the surface element (K). The temperature of any interior node j , at the next
 3358 timestep $i+1$, is defined as:

$$3359 \quad T_j^{i+1} = T_j^i + \frac{\Delta t}{(\rho \cdot c)_j^i \Delta x^2} \cdot \left[\left(\frac{\lambda_{j-1}^i + \lambda_j^i}{2} \right) (T_{j-1}^i - T_j^i) - \left(\frac{\lambda_j^i + \lambda_{j+1}^i}{2} \right) (T_j^i - T_{j+1}^i) \right]$$

3360

EQUATION 26

3361

3362 And the temperature at the unexposed face is defined as:

$$3363 \quad T_N^{i+1} = T_N^i + \frac{2 \cdot \Delta t}{(\rho c)_N^i} \cdot \left[\left(\frac{\lambda_{N-1}^i + \lambda_N^i}{2} \right) \cdot \left(\frac{T_{N-1}^i - T_N^i}{\Delta x} \right) - \sigma \varepsilon (T_N^{i4} - T_{amb}^4) - h_c (T_N^i - T_{amb}) \right]$$

3364

EQUATION 27

3365

3366 Where σ is the Steffen-Boltzmann constant ($5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$), ε is the emissivity of concrete, T_{amb}
 3367 is the ambient temperature on the unexposed side (K), and h_c is the convective heat transfer
 3368 coefficient ($15 \text{ W/m}^2 \cdot \text{K}$).

3369

APPENDIX G. DAMAGE ASSESSMENT FROM PHOTOGRAPHS

| Level | Flat | None | Minor | Moderate | Severe | Major | Lobby Door Damage (All, Some, None) | Notes |
|-------|------------|------|-------|----------|--------|-------|-------------------------------------|--|
| 3 | 7 | | | | | | | |
| | 8 | | | | | | | |
| | 9 | | | | | | | |
| | 10 | | | | | | | Good example of high end Moderate damage, which contains some structural damage. |
| | Lift Lobby | | | | | | | |
| 4 | 11 | | | | | | | |
| | 12 | | | | | | | |
| | 13 | | | | | | | |
| | 14 | | | | | | | |
| | 15 | | | | | | | |
| 5 | 16 | | | | | | | Spalling on most ceilings and walls in this flat; damage to bedroom compartment wall. |
| | Lift Lobby | | | | | | | |
| | 21 | | | | | | | |
| | 22 | | | | | | | |
| | 23 | | | | | | | |
| 6 | 24 | | | | | | | |
| | 25 | | | | | | | |
| | 26 | | | | | | | Spalling on most ceilings and walls in this flat; damage to compartment walls evident, but they are not completely gone. |
| | Lift Lobby | | | | | | | |
| | 31 | | | | | | | Spalling on most ceilings and walls in this flat; no spalling on bedroom walls; damage to compartment walls evident, but they are not completely gone. |
| 7 | 32 | | | | | | | |
| | 33 | | | | | | | |
| | 34 | | | | | | | Bedroom has partial fire-induced window damage but not enough to classify entire flat at moderate damage. |
| | 35 | | | | | | | |
| | 36 | | | | | | | Spalling on livingroom ceiling (not the walls) and on the ceilings and walls in the remainder of the flat; it should be noted that the compartment walls are not as damaged/burned as much as flats 31, 26, and 16, which have been rated as Severe. |
| 8 | Lift Lobby | | | | | | | |
| | 41 | | | | | | | |
| | 42 | | | | | | | Living room has minor fire-induced window damage but not enough to classify as moderate for entire flat. |
| | 43 | | | | | | | |
| | 44 | | | | | | | Lobby door completely gone and hard to say for sure whether it burned completely or not; I would consider this low end Major damage. |
| 9 | 45 | | | | | | | Lobby door completely gone and hard to say for sure whether it burned completely or not; Spalling on all ceilings and walls in this flat; damage to compartment walls compared to flat 44. |
| | 46 | | | | | | | I would consider this middle-to-high end Severe damage based on the spalling on most ceilings and walls coupled with a compartment bedroom wall missing either from burning or post-fire teardown (hard to say for sure). |
| | Lift Lobby | | | | | | | |
| | 51 | | | | | | | Firefighter damage to lobby door; Living room has partial fire-induced window, wall and floor damage but not enough to classify as moderate for entire flat. |
| | 52 | | | | | | | |
| 10 | 53 | | | | | | | Partial fire-induced window damage in the living room, but not enough to classify as moderate for entire flat. |
| | 54 | | | | | | | |
| | 55 | | | | | | | Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions. |
| | 56 | | | | | | | Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions. Some partial fire damage coming from Flats 55 and 56, but not enough to classify as moderate for entire lobby. |
| | Lift Lobby | | | | | | | |
| 11 | 61 | | | | | | | Firefighter damage to lobby door. |
| | 62 | | | | | | | |
| | 63 | | | | | | | Firefighter damage to lobby door; Living room has fire-induced window, wall and floor damage but not enough to classify as moderate for entire flat. |
| | 64 | | | | | | | I would consider this low end Major damage based on the spalling on most ceilings and walls coupled with major interior compartment wall damage; lobby door completely gone; It is unclear if it burned or was simply removed. |
| | 65 | | | | | | | Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions. |
| 12 | 66 | | | | | | | Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions. |
| | Lift Lobby | | | | | | | |
| | 71 | | | | | | | Living room and a bedroom both have fire-induced window damage but not enough to classify as moderate for entire flat. |
| | 72 | | | | | | | Lobby door frame burned. |
| | 73 | | | | | | | I would consider this low end Major damage based on the spalling on most ceilings and walls coupled with major interior compartment wall damage; lobby door completely gone; It is unclear if it burned or was simply removed. |
| 13 | 74 | | | | | | | Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions. |
| | 75 | | | | | | | Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions. |
| | 76 | | | | | | | Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions with major compartment wall damage. |
| | Lift Lobby | | | | | | | Spalling on ceiling and walls. |
| | 81 | | | | | | | Firefighter damage to lobby door. |
| 14 | 82 | | | | | | | Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions. Light spalling on ceiling in entry way ceiling and peeling ceiling in the living room lead me to rate this as Moderate. |
| | 83 | | | | | | | |
| | 84 | | | | | | | I would consider this middle-to-high end Severe damage based on the spalling on most ceilings and walls with a clean bedroom; lobby door completely gone; It is unclear if it burned or was simply removed. |
| | 85 | | | | | | | Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions. |
| | 86 | | | | | | | Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions. |
| 15 | Lift Lobby | | | | | | | Lobby door completely gone; it is unclear if it burned or was simply removed; post-flashover conditions. |
| | Stair | | | | | | | Spalling on ceiling and walls. |
| 16 | 87 | | | | | | | Soot on the door but no damage visible. |
| | 88 | | | | | | | |

JTOR00000001 0180

